SIMULATION AND SPEED CONTROL OF INDUCTION MOTOR DRIVES

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CERTIFICATE

This is to certify that the thesis entitled, **"Simulation and Speed Control of Induction Motor Drives"** submitted by **AMITPAL SINGH I. S. BHATIA (108EE054), VINIT KUMAR GUPTA (108EE059)** and **SOURAV ANAND SETHI (108EE077)** in partial fulfilment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

Induction motors are the most widely used electrical motors due to their reliability, low cost and robustness. However, induction motors do not inherently have the capability of variable speed operation. Due to this reason, earlier dc motors were applied in most of the electrical drives. But the recent developments in speed control methods of the induction motor have led to their large scale use in almost all electrical drives.

Out of the several methods of speed control of an induction such as pole changing, frequency variation, variable rotor resistance, variable stator voltage, constant V/f control, slip recovery method etc., the closed loop constant V/f speed control method is most widely used. In this method, the V/f ratio is kept constant which in turn maintains the magnetizing flux constant so that the maximum torque remains unchanged. Thus, the motor is completely utilized in this method.

During starting of an induction motor, the stator resistance and the motor inductance (both rotor and stator) must be kept low to reduce the steady state time and also to reduce the jerks during starting. On the other hand, higher value of rotor resistance leads to lesser jerks while having no effect on the steady state time.

The vector control analysis of an induction motor allows the decoupled analysis where the torque and the flux components can be independently controlled (just as in dc motor). This makes the analysis easier than the per phase equivalent circuit.

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LIST OF SYMBOLS

IM	Induction Motor
R_s	Stator Resistance
R_r	Rotor Resistance
R_r’	Rotor Resistance Referred to Stator side
X_s	Stator Reactance
X_r	Rotor Reactance
X_r’	Rotor Reactance Referred to Stator side
X_m	Leakage Inductance
I_1	Stator Current
I_2	Rotor Current
I_2’	Rotor Current Referred to Stator side
I_m	Magnetizing Current
V_0	Stator Voltage
s	Slip
ω_s	Synchronous Speed
ω_m	Rotor Speed (Machine Speed)
Ω_s	Average Synchronous Speed (in RPM)
f	Supply Frequency
p	No. of Poles
P_g	Air-gap Power
P_{cu}	Copper loss in the machine
P_m	Mechanical Power output of the machine
T	Torque Developed by the motor
s_m	Slip at maximum torque
T_{max}	Maximum Torque
V_d	DC Link Voltage
ω_{ref}	Reference Speed

ω_{sl}	Slip Speed
ω_f	Rotor Speed at Frequency f
Y_d	Space Vector in d-axis
Y_q	Space Vector in q-axis
Y_a	Space Vector of a-phase
Y_b	Space Vector of b-phase
Y_c	Space Vector of c-phase
V_{qs}	q-axis Stator Voltage with stationary frame
V_{ds}	d-axis Stator Voltage with stationary frame
I_{qs}	q-axis Stator Current with stationary frame
I_{ds}	d-axis Stator Current with stationary frame
I_{qr}	q-axis Rotor Current with stationary frame
I_{dr}	d-axis Rotor Current with stationary frame
λ_{ds}	d-axis Stator flux with stationary frame
λ_{qs}	q-axis Stator flux with stationary frame
λ_{dr}	d-axis Rotor flux with stationary frame
λ_{qr}	q-axis Rotor flux with stationary frame
λ_s	q-axis Rotor flux with stationary frame
L_s	Stator Self-Inductance
L_r	Rotor Self-Inductance
L_m	Stator Mutual-Inductance
I_s'	Complex Conjugate of Stator Current
P_i	Instantaneous Active Power
Q_i	Instantaneous Reactive Power

CHAPTER I

INTRODUCTION

Be it domestic application or industry, motion control is required everywhere. The systems that are employed for this purpose are called drives. Such a system, if makes use of electric motors is known as an electrical drive. In electrical drives, use of various sensors and control algorithms is done to control the speed of the motor using suitable speed control methods. The basic block diagram of an electrical drive is shown below:

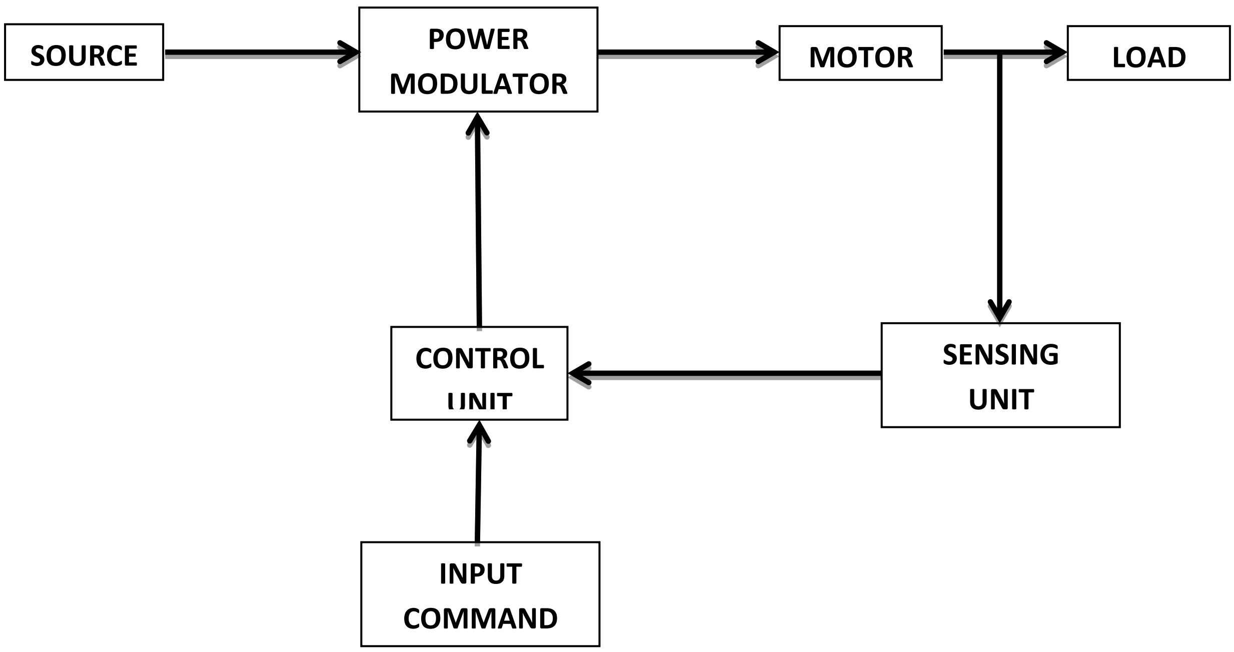

Figure 1.1: Block diagram of an electrical drive

Earlier only dc motors were employed for drives requiring variable speeds due to ease of their speed control methods. The conventional methods of speed control of an induction motor were either too expensive or too inefficient thus restricting their application to only constant speed drives. However, modern trends and development of speed control methods of an induction motor have increased the use of induction motors in electrical drives extensively.

In this paper, we have studied the various methods of speed control of a 3-ϕ induction motor and compared them using their Torque-Speed characteristics. Also the transients during the starting of a 3-ϕ induction motor were studied using MATLAB Simulink and the effects of various parameters such as rotor and stator resistances and inductances were analysed. Also different control algorithms such as P, PI and PID control were studied by simulating them in MATLAB Simulink and were compared.

CHAPTER 2

LITERATURE REVIEW

2.1 Three phase induction motor and their Torque-Speed analysis

Based on the construction of the rotor, a 3-ϕ induction motor can be categorized into two types:

i. Squirrel Cage Induction Motor
ii. Wound Rotor or Slip Ring Induction Motor

The stator of both types of motors consists of a three phase balanced distributed winding with each phase mechanically separated in space by 120 degrees from the other two phase windings. This gives rise to a rotating magnetic field when current flows through the stator.

In squirrel cage IM, the rotor consists of longitudinal conductor bars which are shorted at ends by circular conducting rings. Whereas, the wound rotor IM has a 3-ϕ balanced distributed winding even on the rotor side with as many number of poles as in the stator winding.

Considering the three phases to be balanced, the analysis of a 3-ϕ induction motor can be done by analysing only one of the phases. The per phase equivalent circuit of an induction motor is shown below:

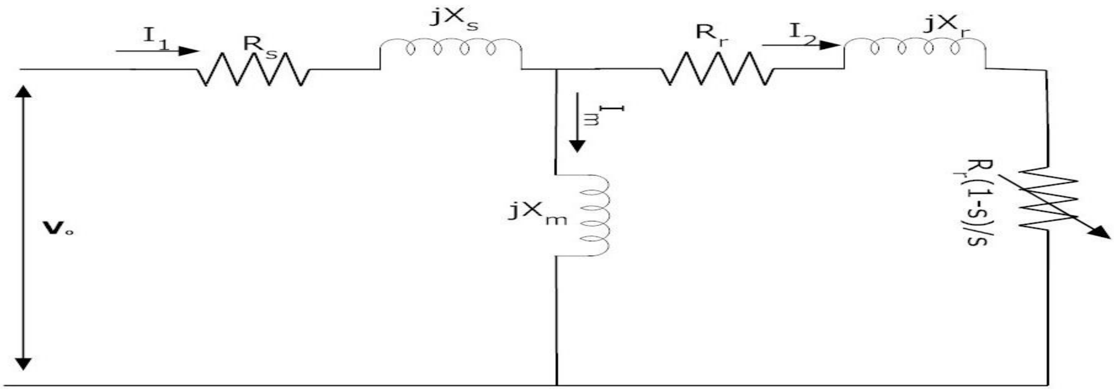

Figure 2.1: Per phase equivalent circuit of a 3-ϕ induction motor

R_2 and X_2 are the stator referred values of rotor resistance R_1 and rotor reactance X_1. Slip is defined by

$$\mathbf{s = (\omega_s - \omega_m)/ \omega_s} \qquad (2.1)$$

where, ω_m and ω_s are rotor and synchronous speeds, respectively.

Further, $\omega_s = 120f/p$ **rpm** (2.2)

Where f and p are supply frequency and number of poles, respectively.

Since, stator impedance drop is generally negligible compared to terminal voltage V, the equivalent circuit can be simplified to that shown below:

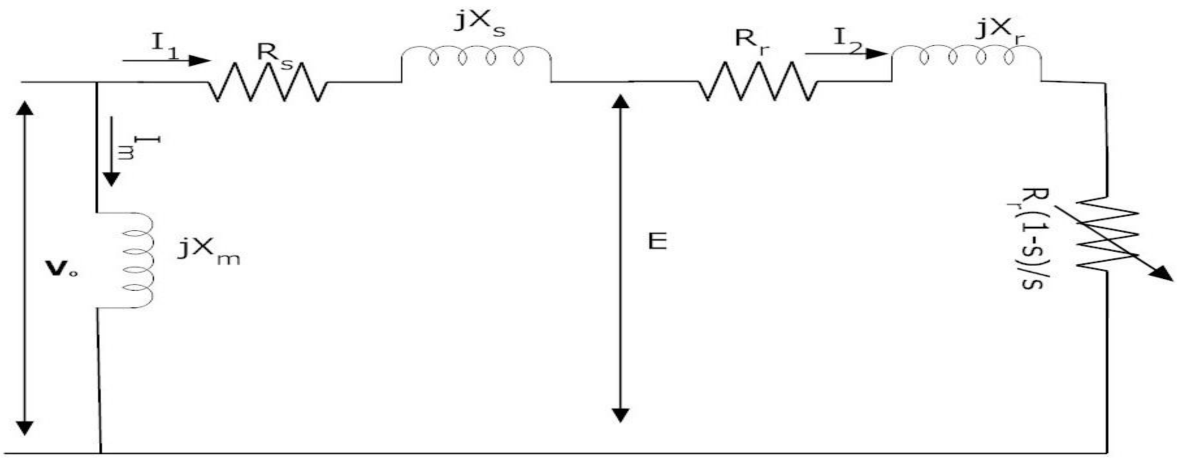

Figure 2.2: Per phase approximate equivalent circuit of a 3-ϕ induction motor

Rotor current

$$I_2 = \frac{Vo}{[\left(R_s + \frac{R_r}{s}\right) + j(X_s + X_r)]} \tag{2.3}$$

Power transferred to rotor (or air-gap power)

$$P_g = 3I_2\frac{R_r}{s} \tag{2.4}$$

Rotor copper loss is

$$P_{cu} = 3I_2R_r \tag{2.5}$$

Electrical power converted into mechanical power

$$P_m = P_g - P_{cu} = 3I^2{}_2R_r\left(\frac{1-s}{s}\right) \tag{2.6}$$

Torque developed by motor

$$T = P_m/\omega_m \tag{2.7}$$

Thus,

$$T = \frac{3I_2{}^2 R_r}{s\omega_s} \tag{2.8}$$

Substituting the value of I_2 into the above equation, we get,

$$T = \frac{\left(\frac{3Vo^2 R_r}{s}\right)}{\omega_s\left[\left(R_s + \frac{R_r}{s}\right)^2 + (X_s + X_r)^2\right]} \tag{2.9}$$

Differentiating T with respect to s and equating to zero gives the slip for maximum torque

$$s_m = \pm \frac{R_r}{\sqrt{[R_s{}^2 + (X_s + X_r)^2]}} \tag{2.10}$$

Substituting S_m in T gives the value of maximum torque, thus

$$T_{max} = \frac{3Vo^2}{2\omega_s\left[R_r \pm \sqrt{\left(R_r{}^2 + (X_s + X_r)^2\right)}\right]} \tag{2.11}$$

CHAPTER 3

TRANSIENTS DURING STARTING OF A 3-ϕ INDUCTION MOTOR

A model of a 3-ϕ induction motor was setup in MATLAB SIMULINK and the rotor and stator currents, speed, electromagnetic torque and the Torque-Speed characteristics were observed with different values of rotor and stator resistances and impedances.

The SIMULINK model is shown below.

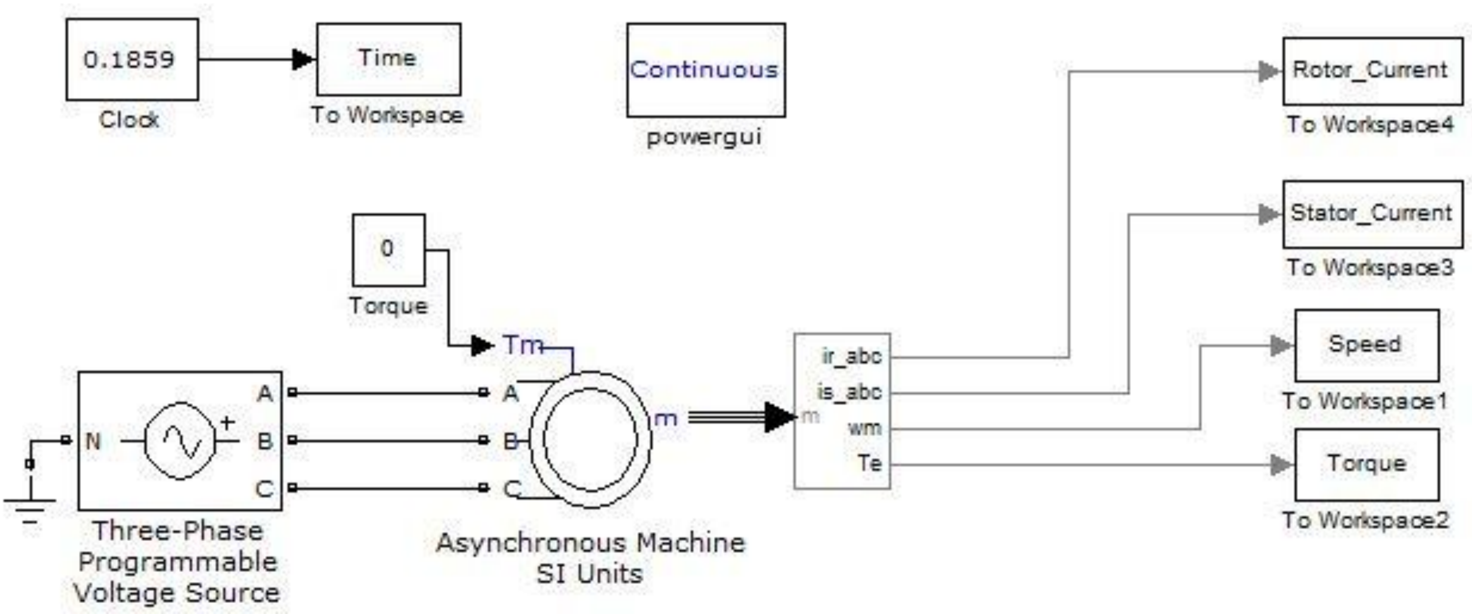

Figure 3.1: SIMULINK model of a 3-ϕ Induction motor

The different machine details followed by their corresponding outcomes are shown in this chapter.

It should be noted that all the simulations were made for Zero Load Torque. However, the inertia and friction were taken into consideration.

3.1 Low stator inductance (~0.05 mH)

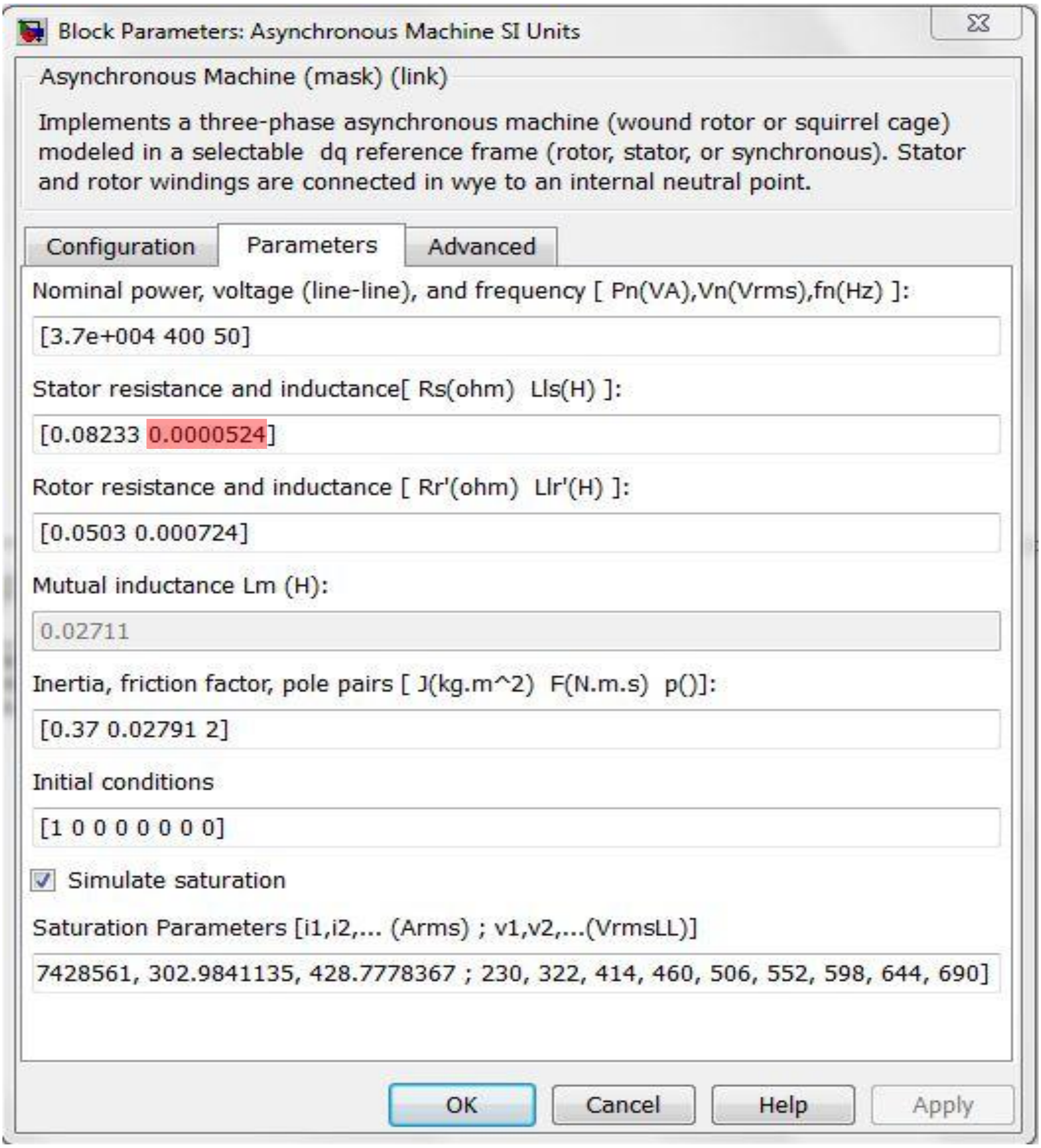

Figure 3.2: Parameters of 3-ϕ induction motors (Low stator impedance)

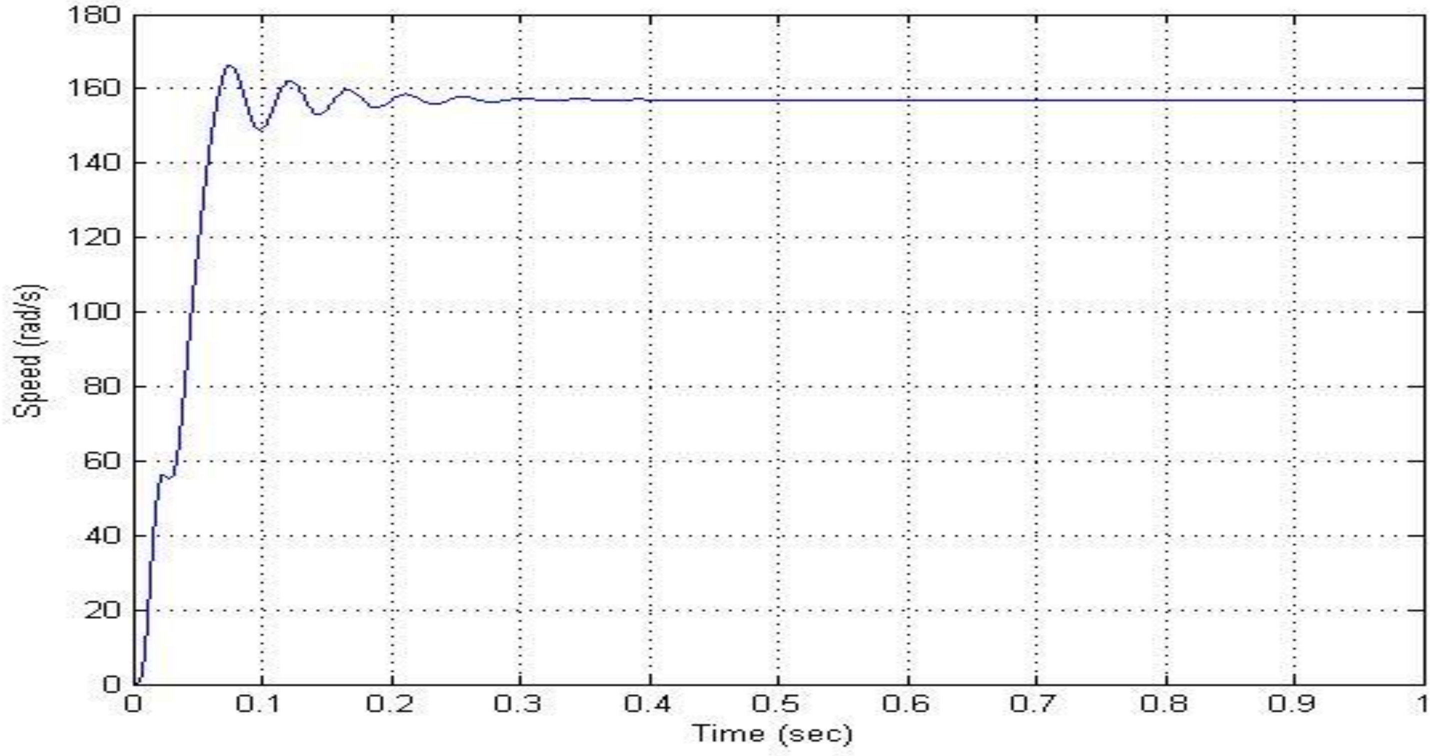

Figure 3.3: Rotor Speed Vs Time graph for machine parameters as in Figure 3.2

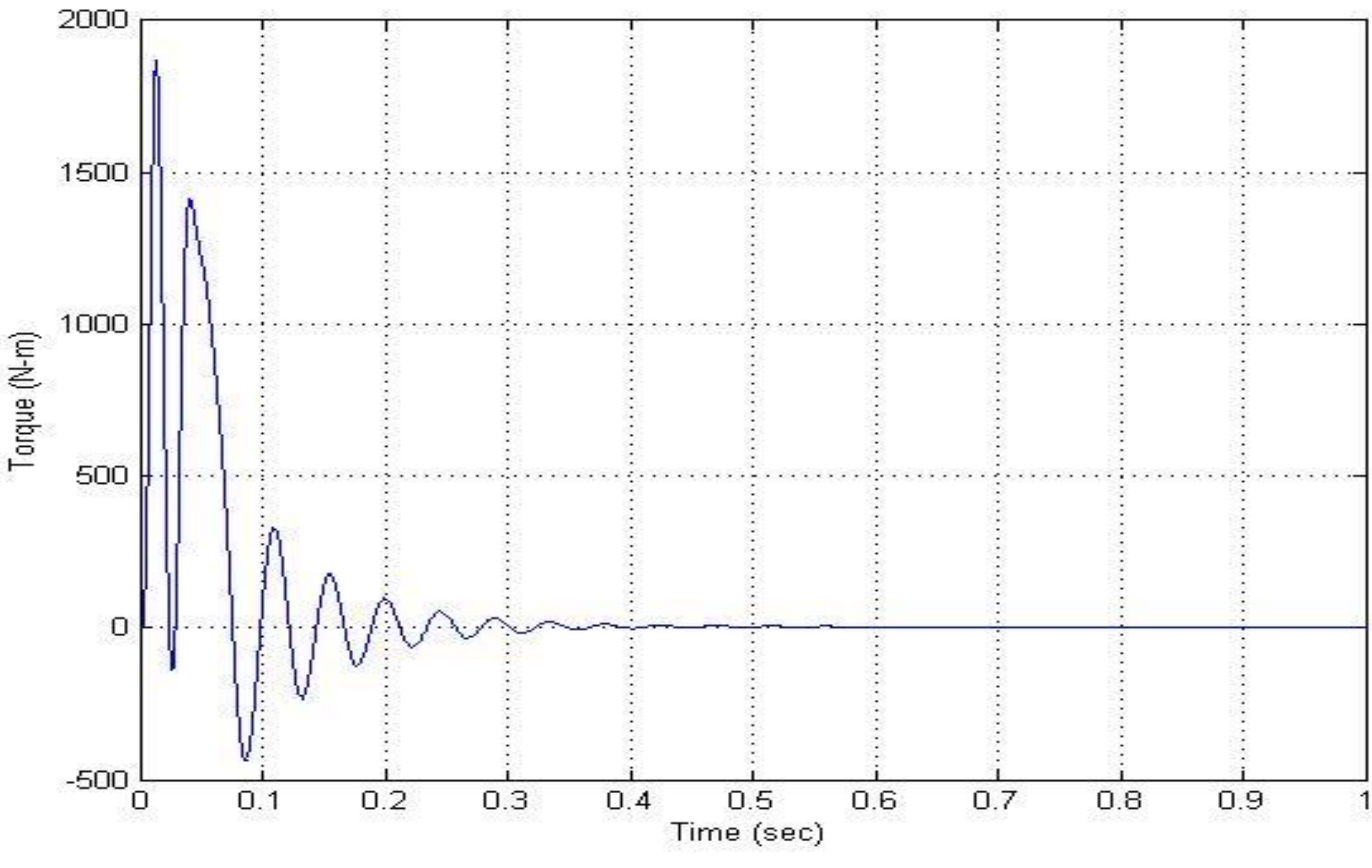

Figure 3.4: Torque Vs Time graph for machine parameters as in Figure 3.2

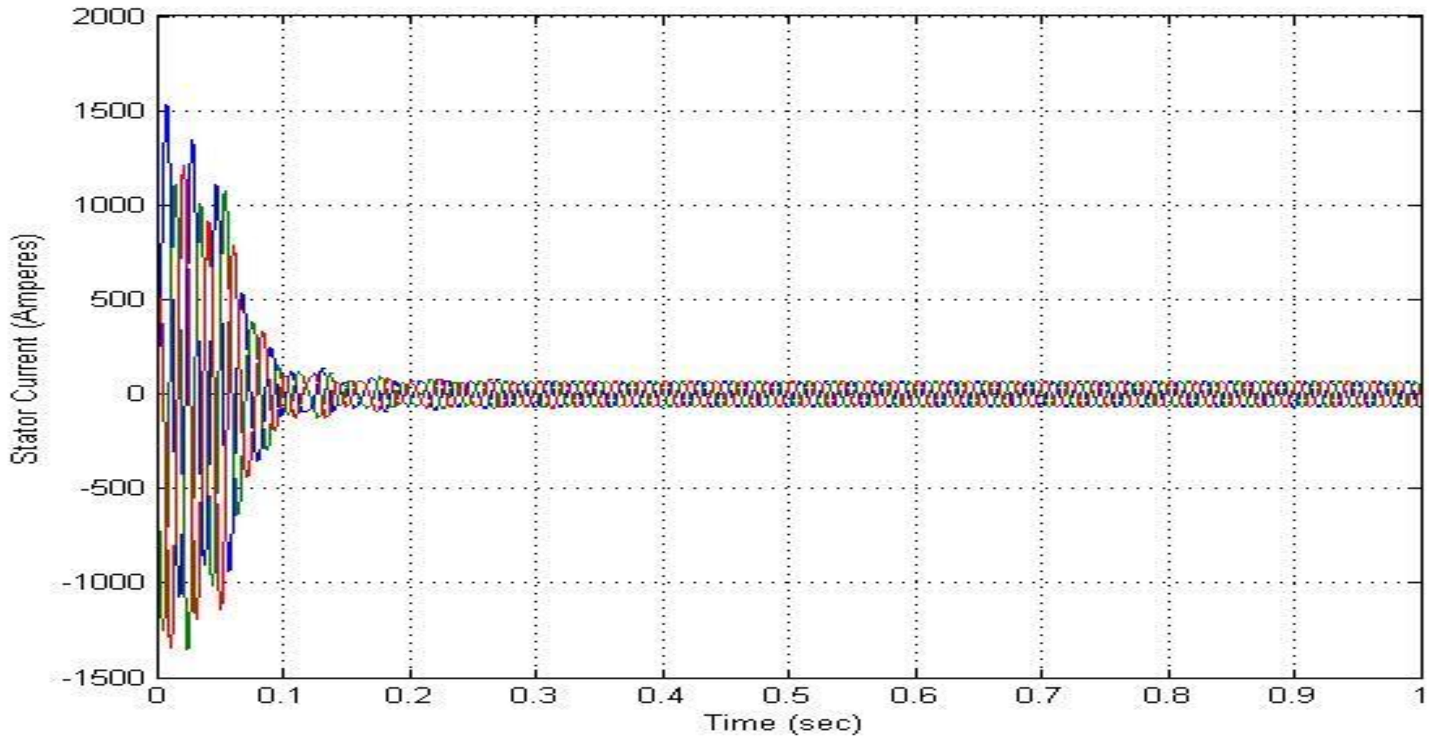

Figure 3.5: Stator Current Vs Time graph for machine parameters as in Fig 3.2

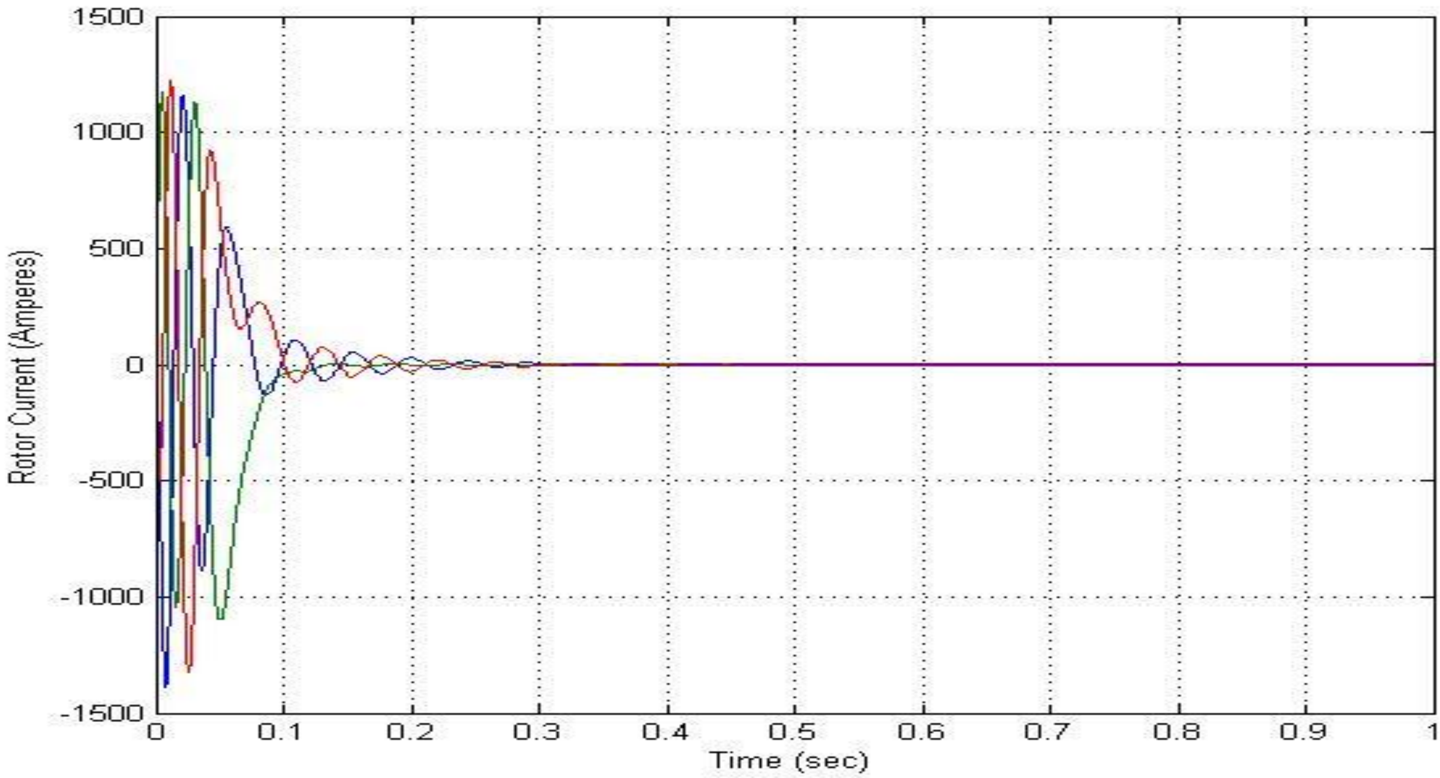

Figure 3.6: Rotor Current Vs Time graph for machine parameters as in Fig 3.2

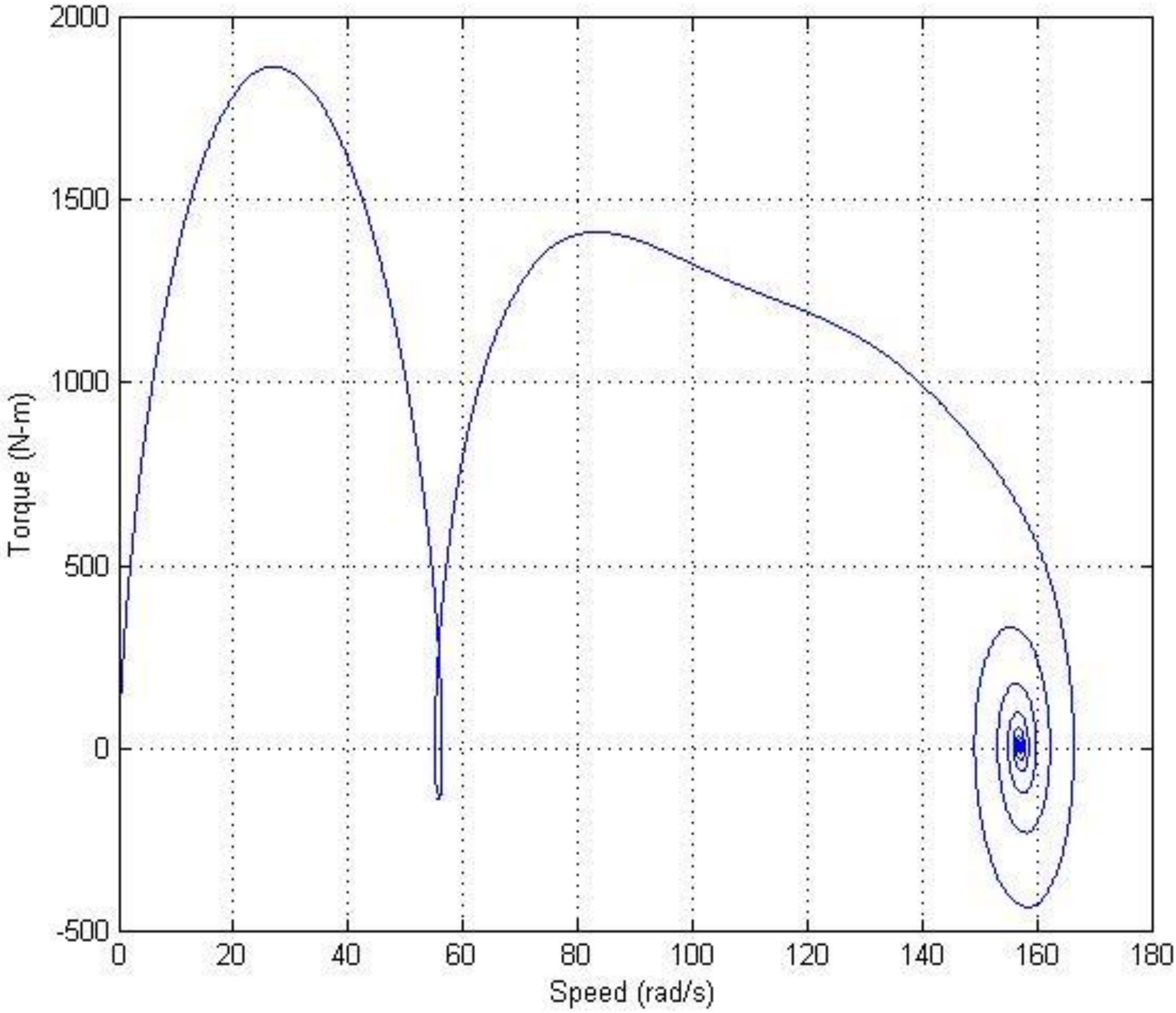

Figure 3.7: Torque-Speed Characteristics for machine parameters as in Fig 3.2

3.2 Medium stator inductance (~0.7 mH)

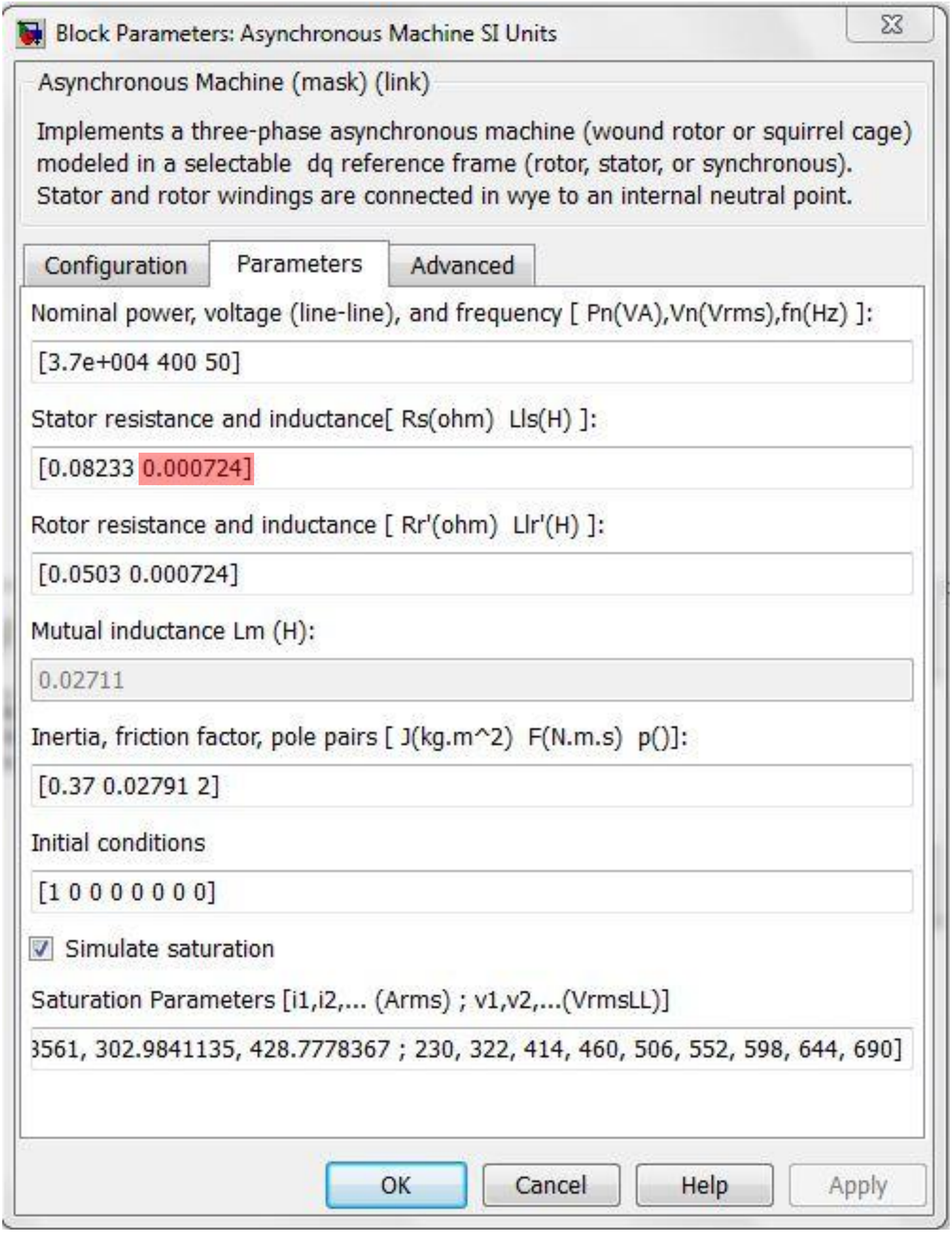

Figure 3.8: Parameters of 3-ϕ induction motors (Medium stator inductance)

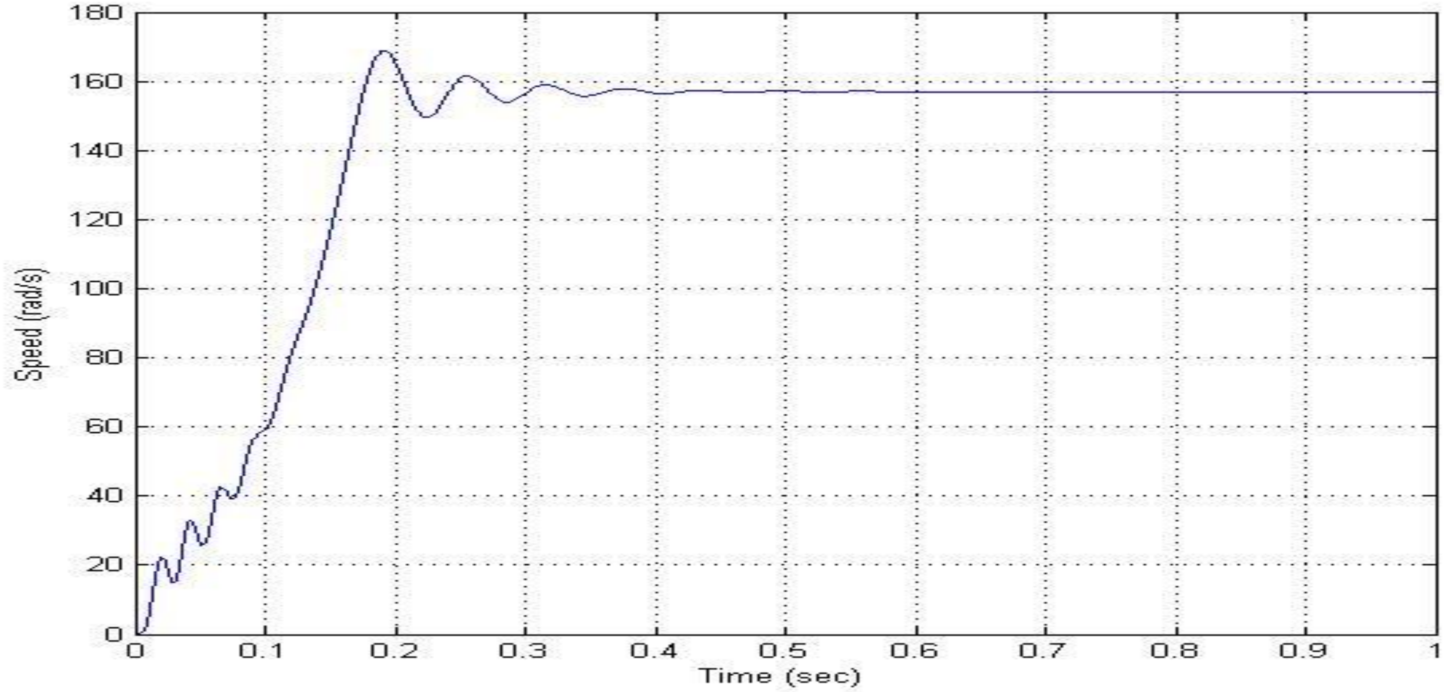

Figure 3.9: Rotor Speed Vs Time graph for machine parameters as in Figure 3.8

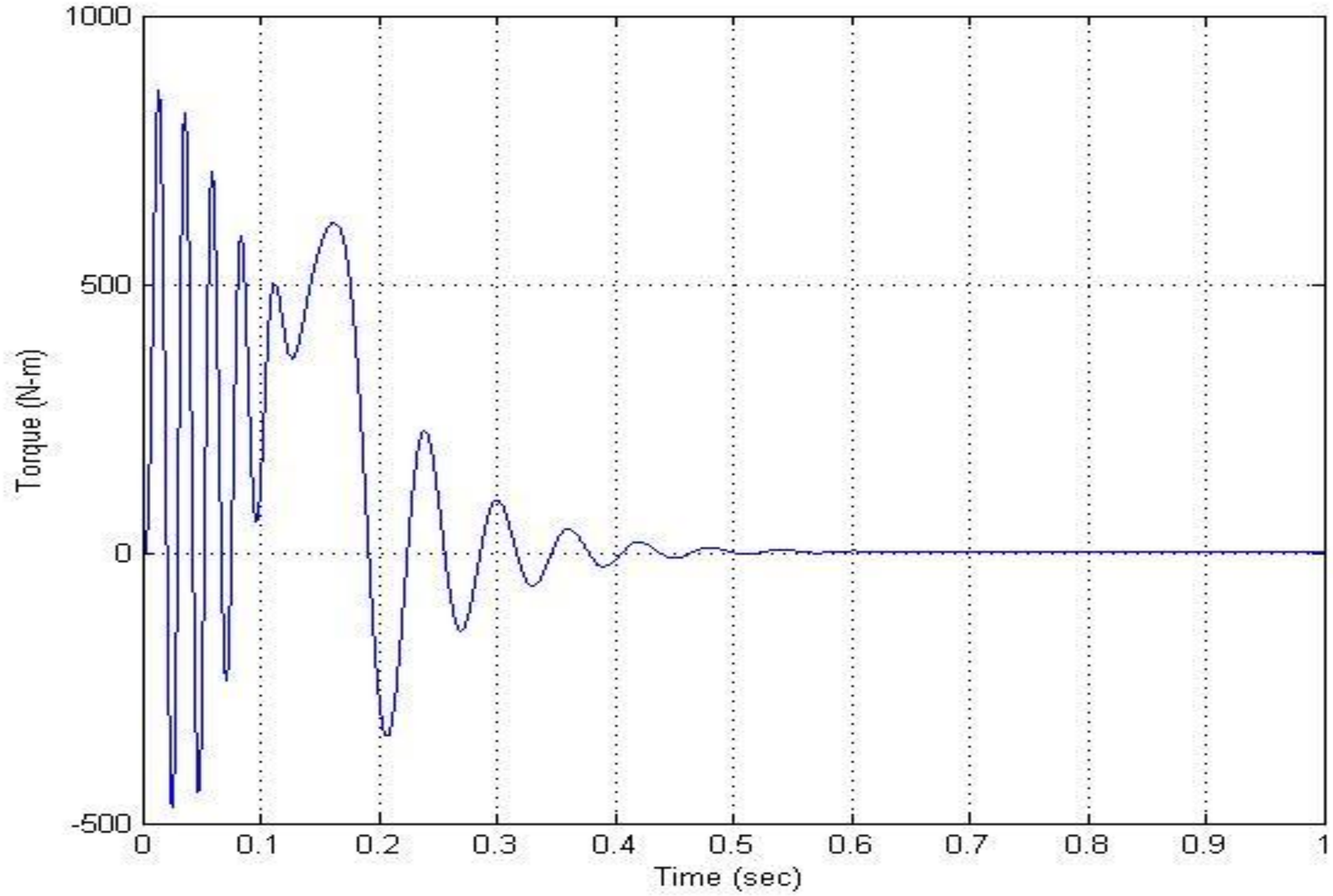

Figure 3.10: Torque Vs Time graph for machine parameters as in Figure 3.8

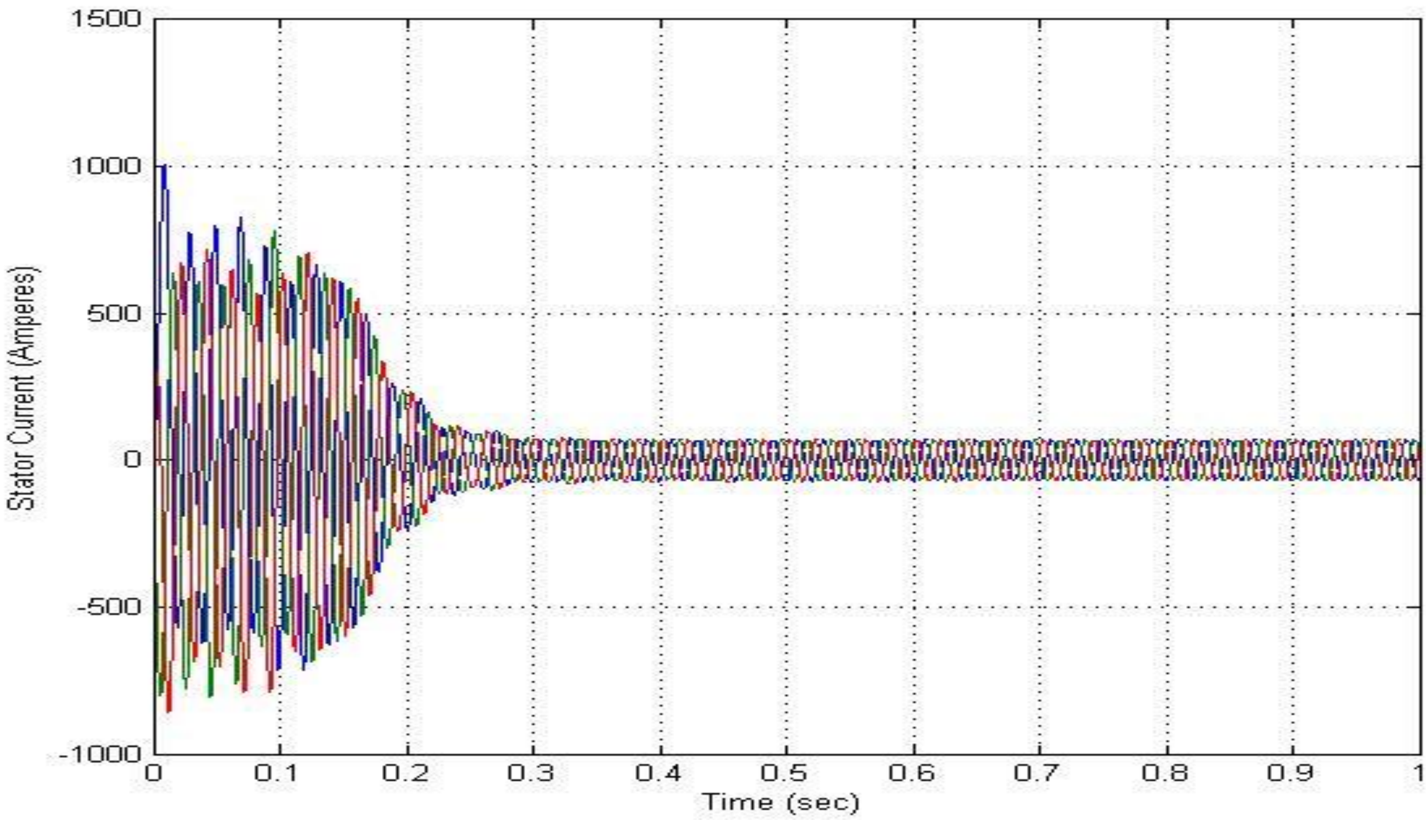

Figure 3.11: Stator Current Vs Time graph for machine parameters as in Fig 3.8

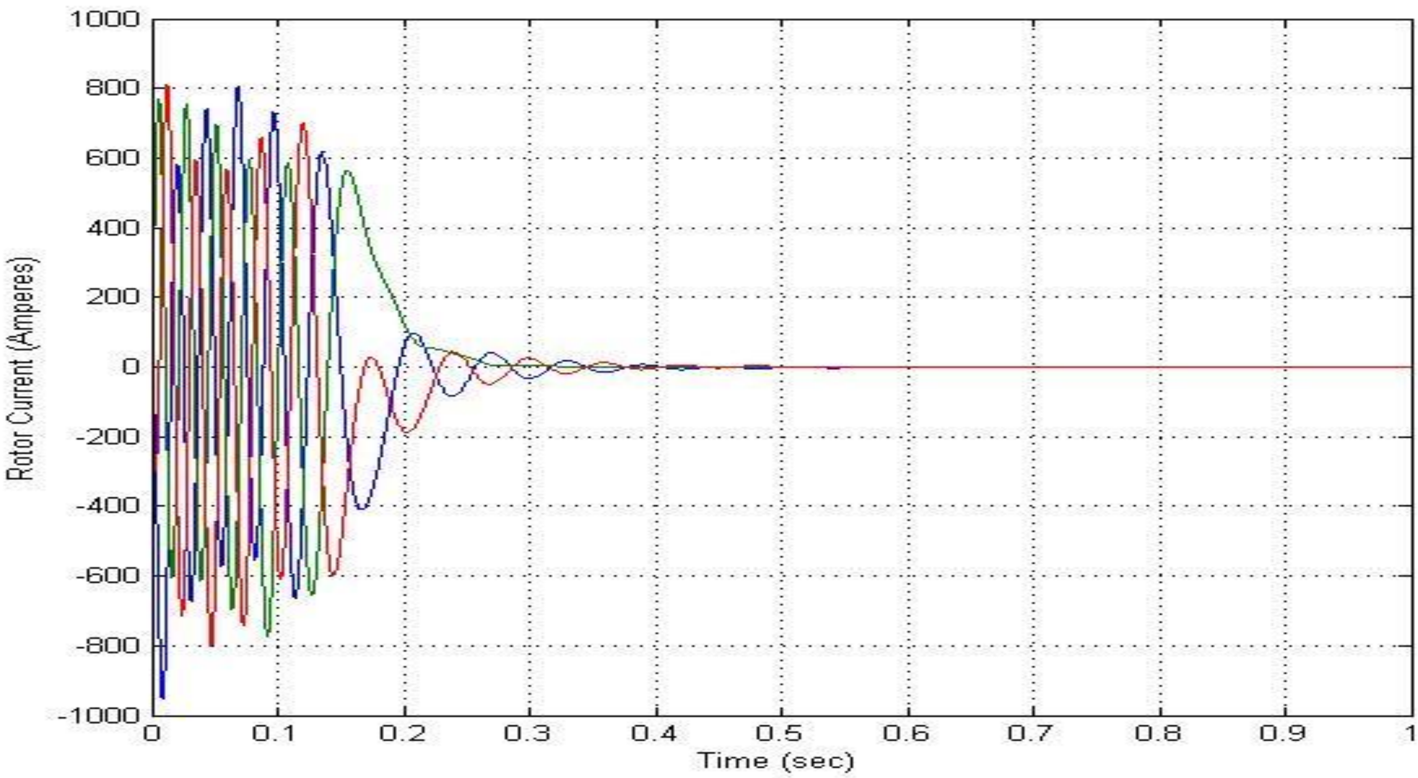

Figure 3.12: Rotor Current Vs Time graph for machine parameters as in Fig 3.8

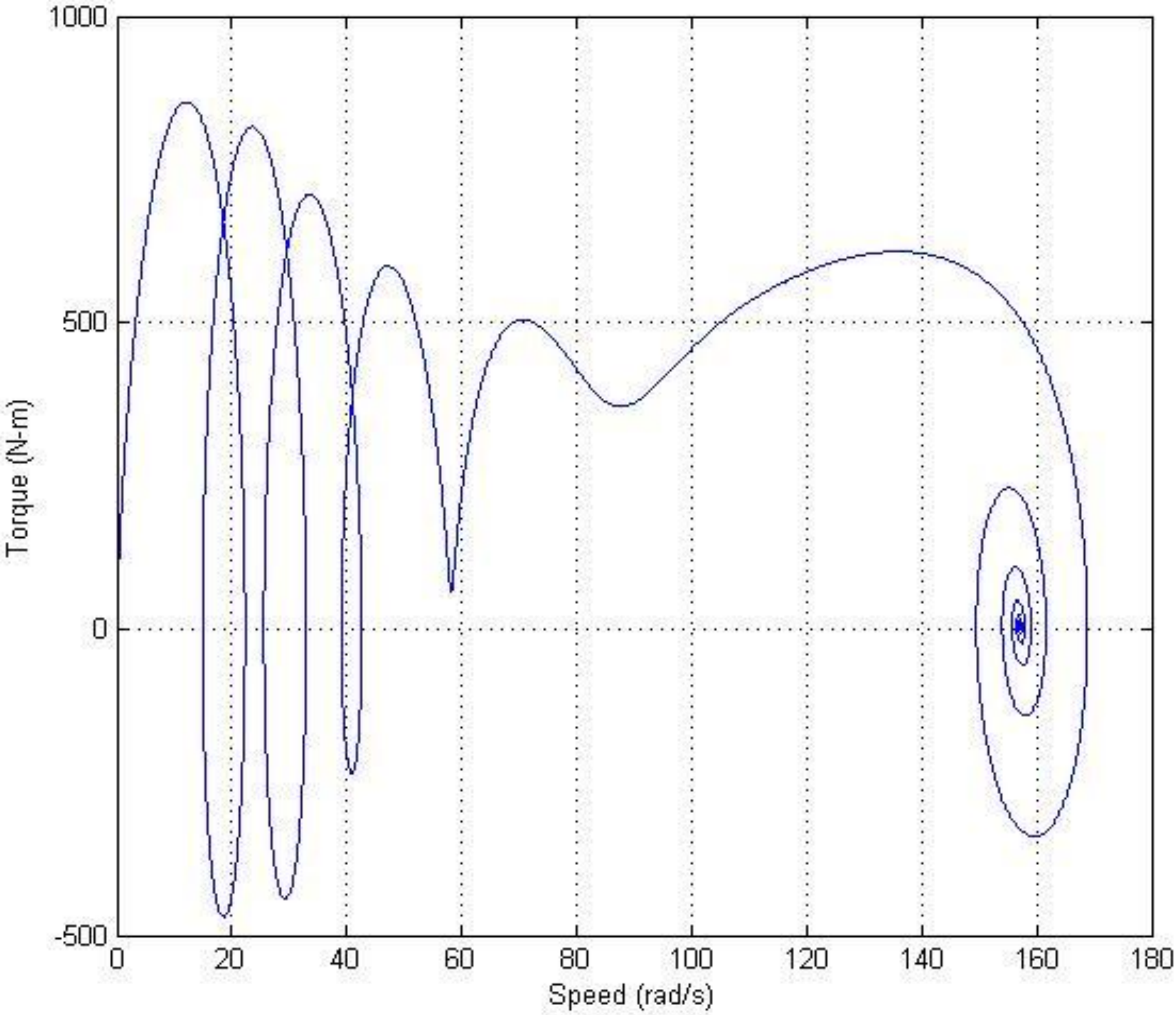

Figure 3.13: Torque-Speed Characteristics for machine parameters as in Fig 3.8

3.3 High stator inductance (~2 mH)

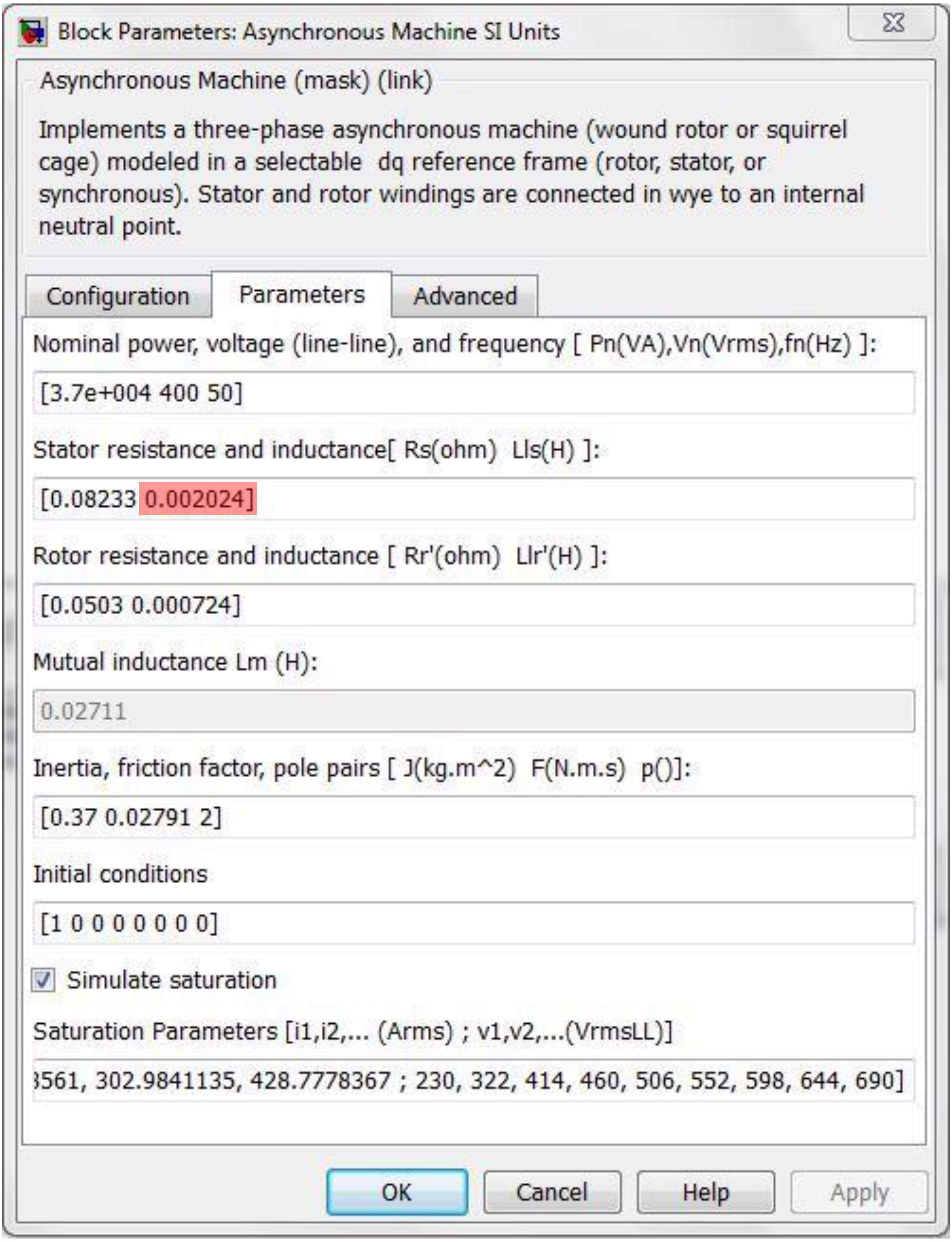

Figure 3.14: Parameters of 3-ϕ induction motors (High stator inductance)

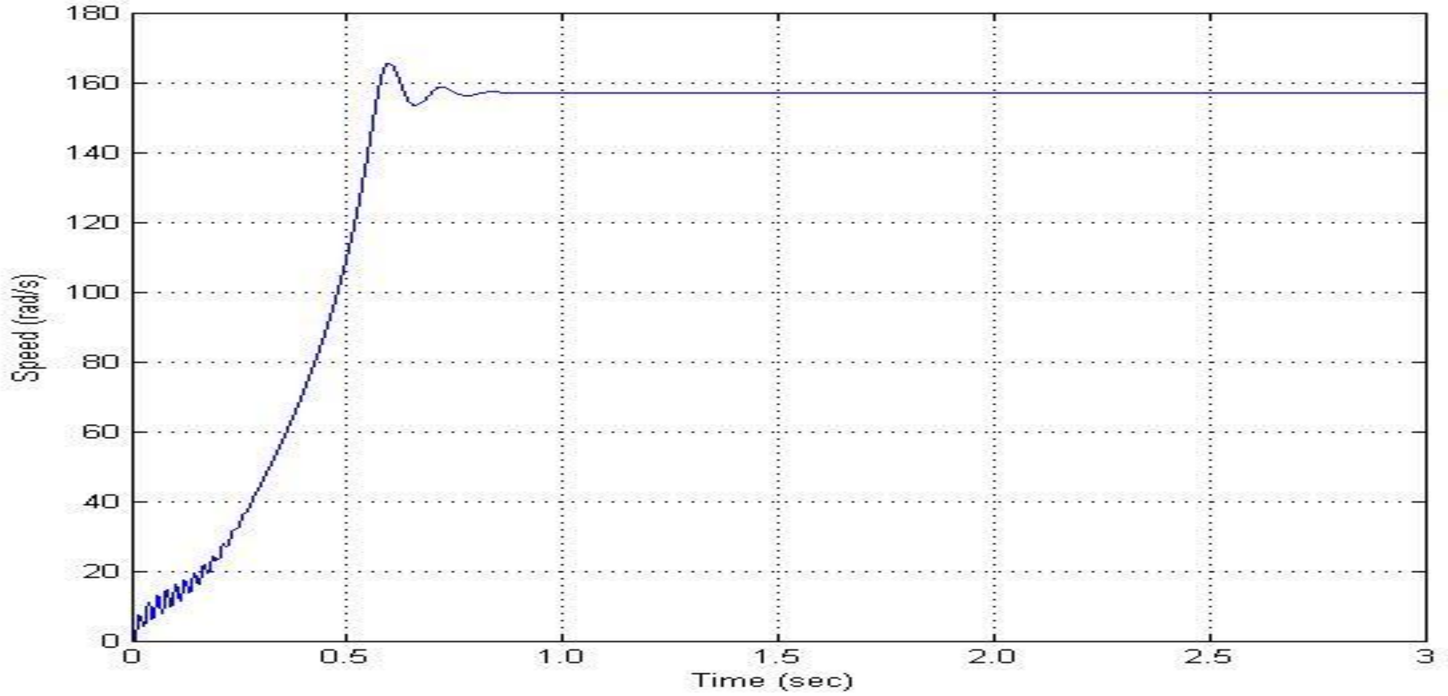

Figure 3.15: Rotor Speed Vs Time graph for machine parameters as in Fig 3.14

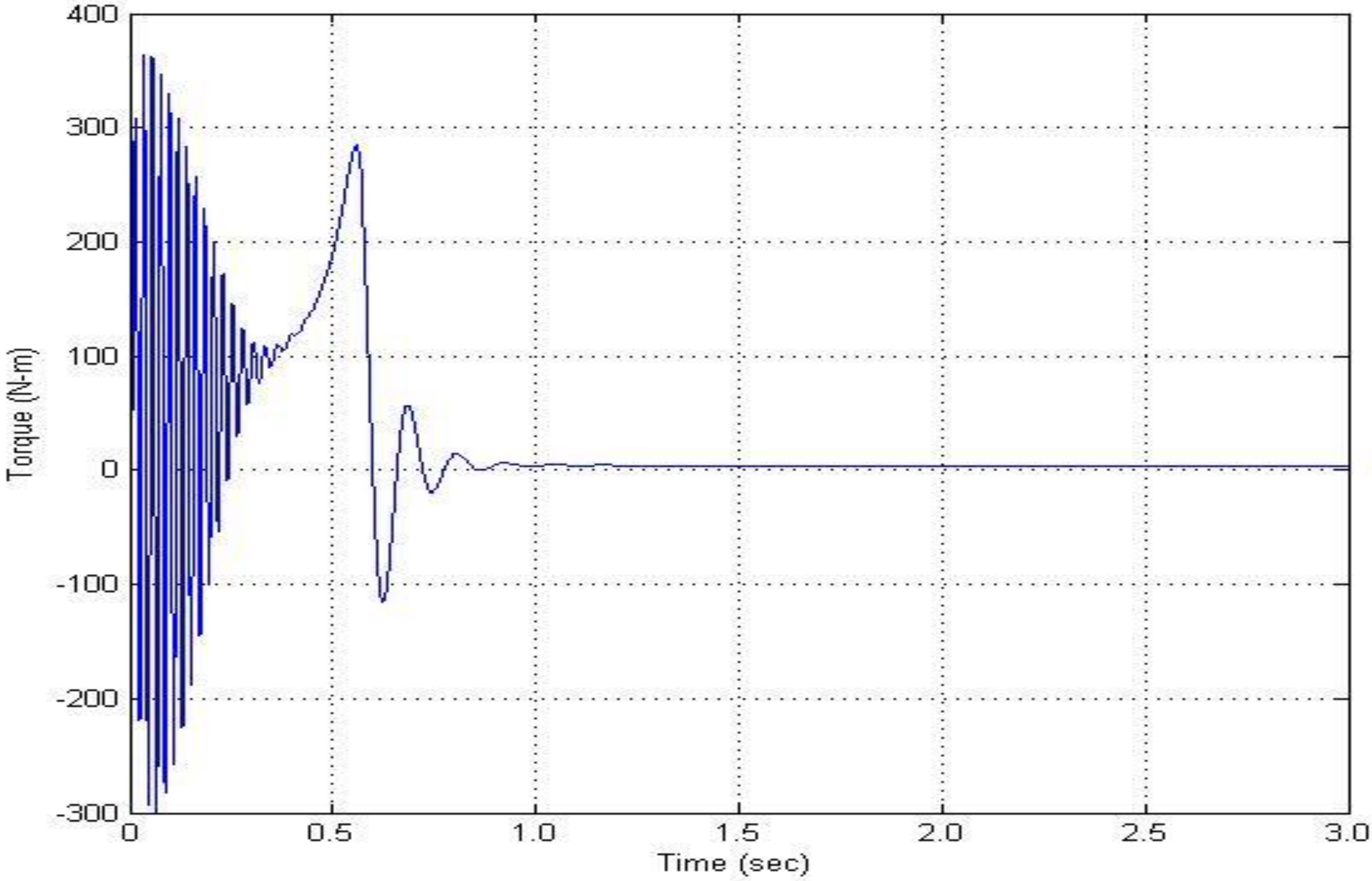

Figure 3.16: Torque Vs Time graph for machine parameters as in Figure 3.14

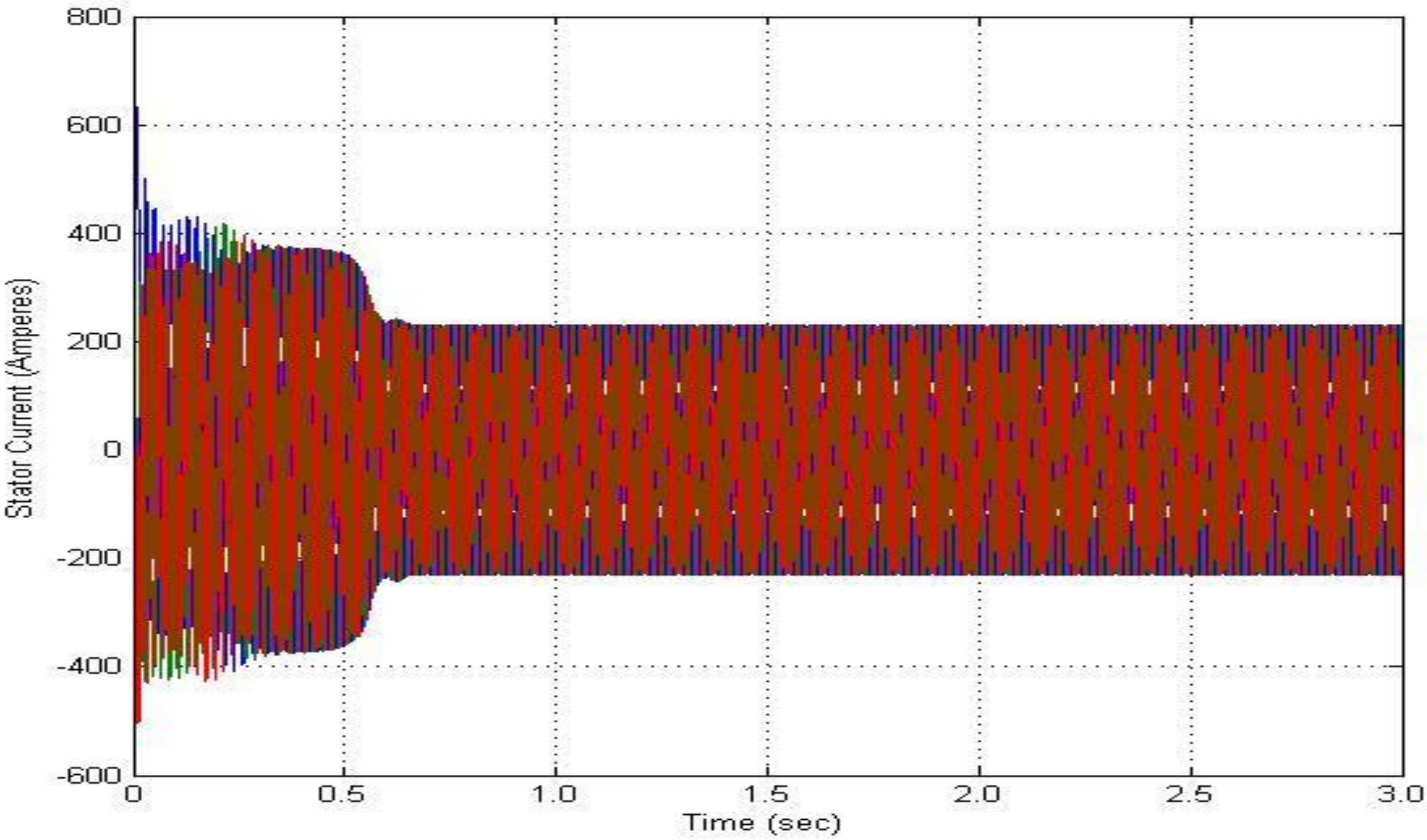

Figure 3.17:Stator Current Vs Time graph for machine parameters as in Fig 3.14

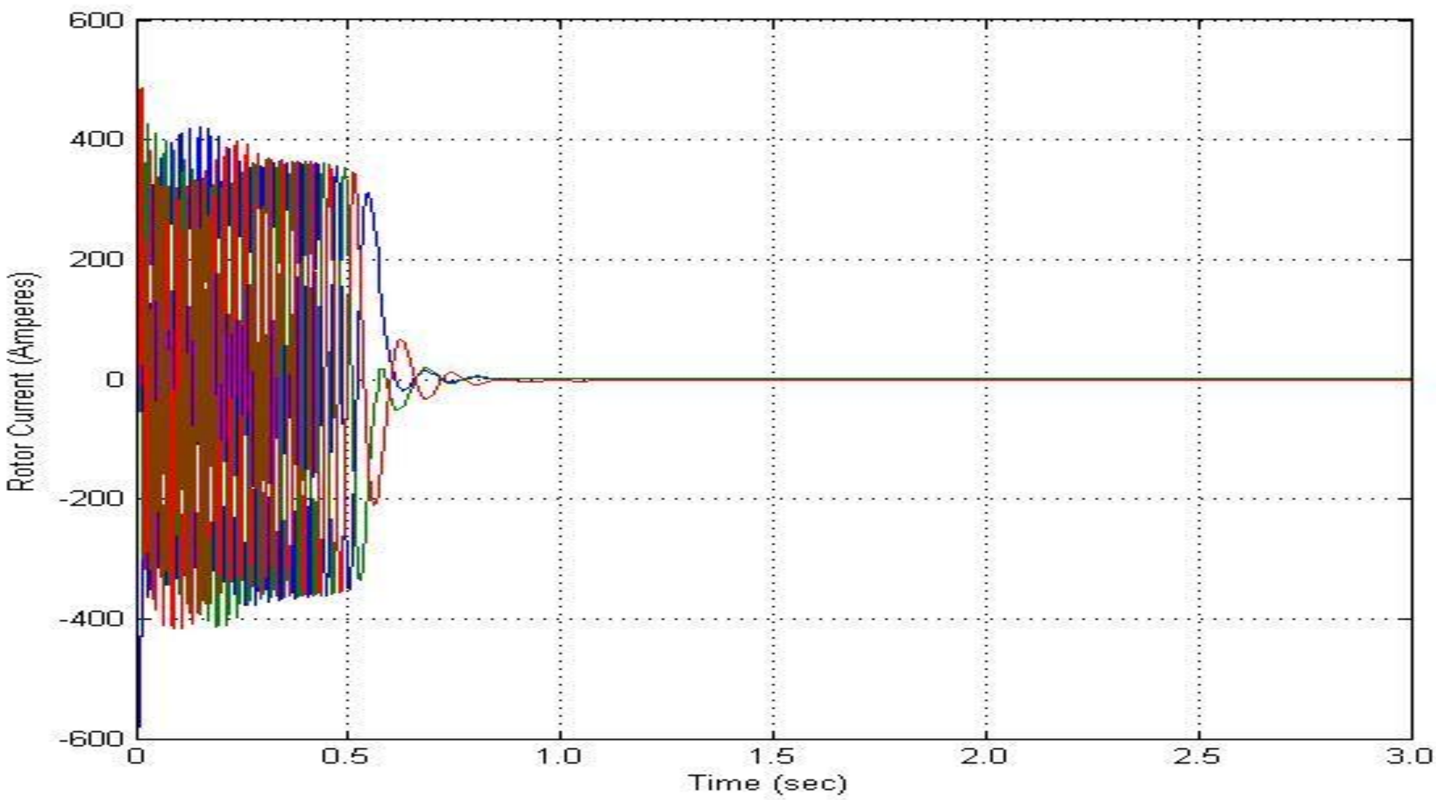

Figure 3.18:Rotor Current Vs Time graph for machine parameters as in Fig 3.14

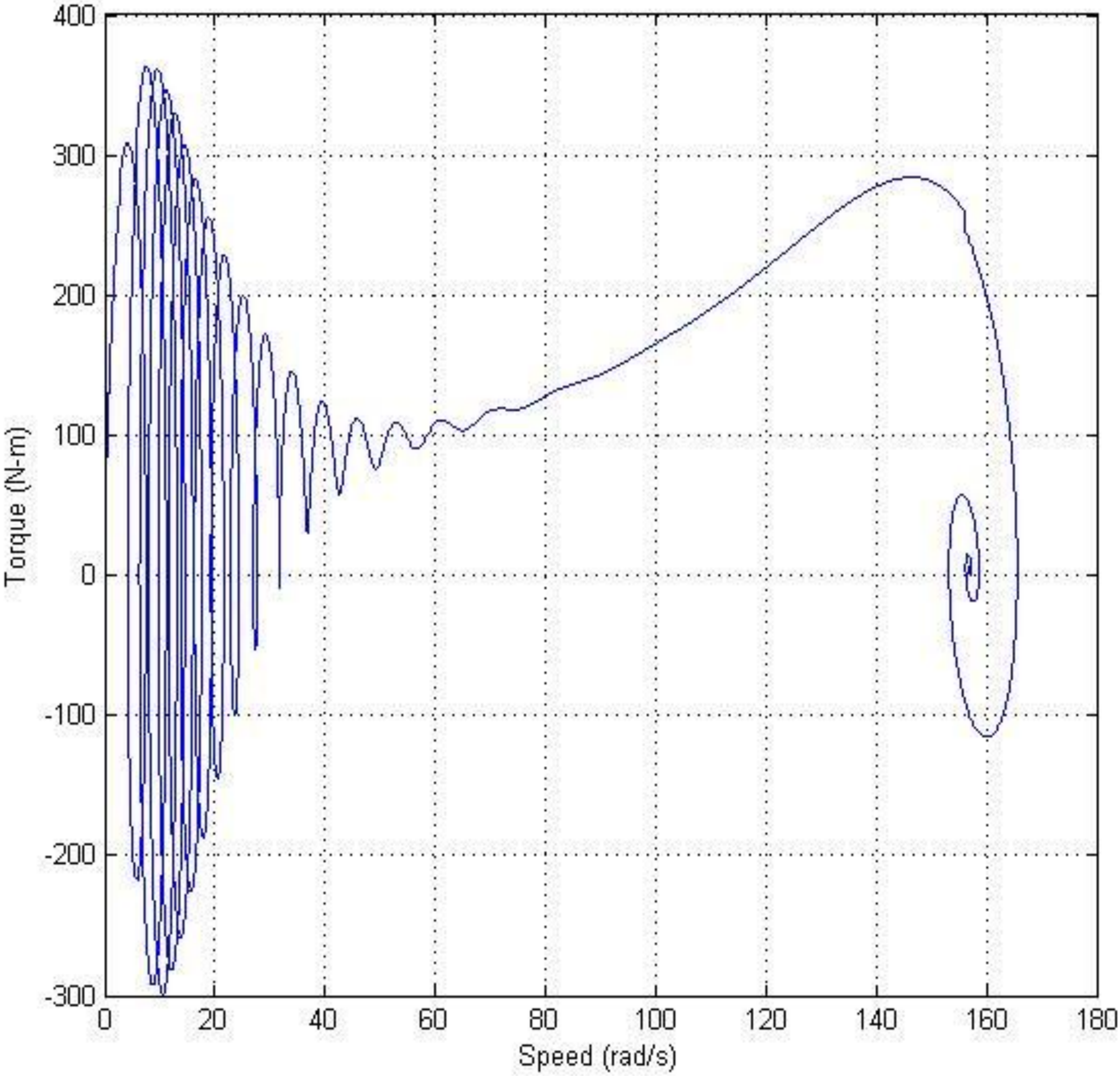

Figure 3.19:Torque-Speed Characteristics for machine parameters as in Fig 3.14

3.4 Low Rotor Resistance (~0.1 Ω)

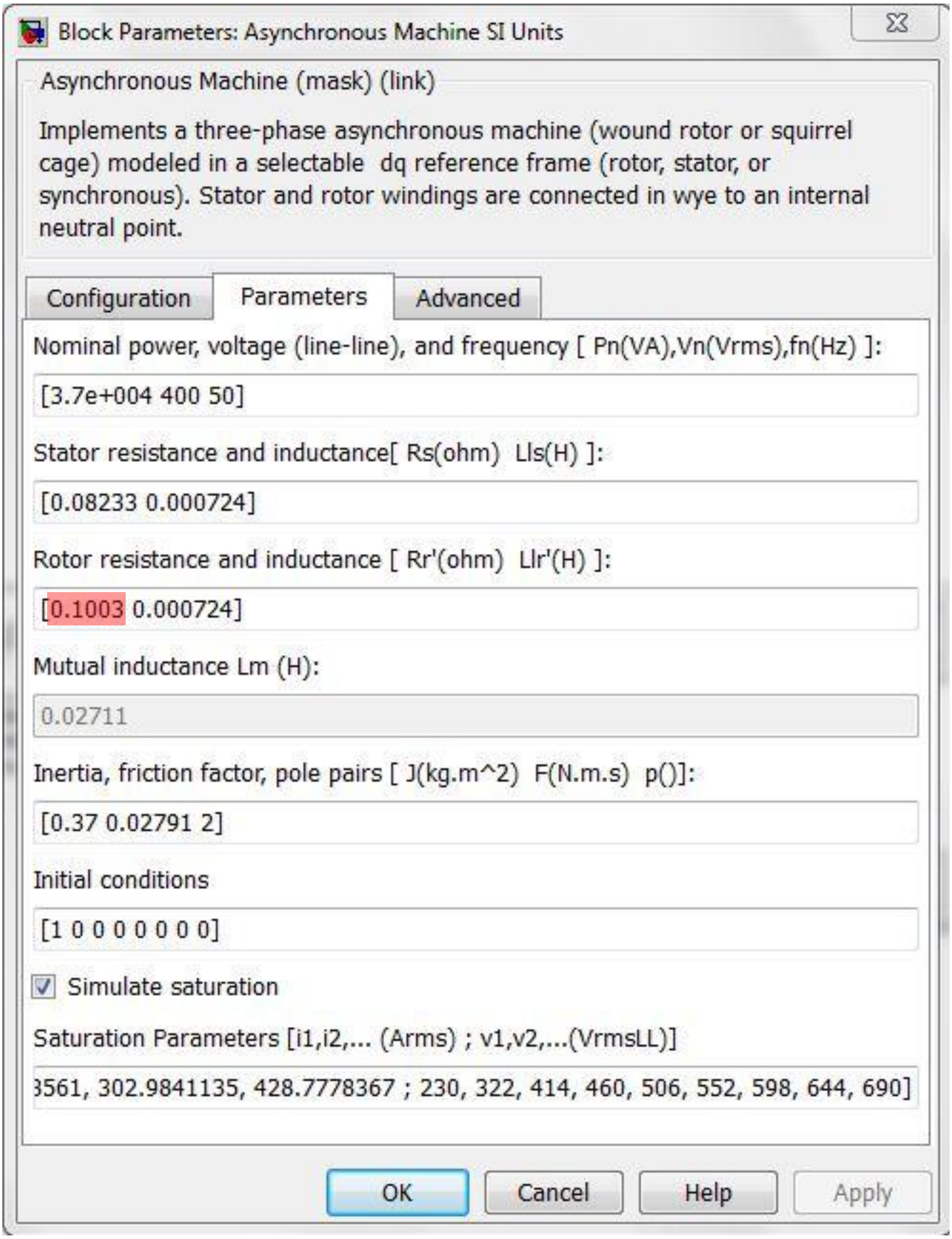

Figure 3.20: Parameters of 3-ϕ induction motors (Low Rotor Resistance)

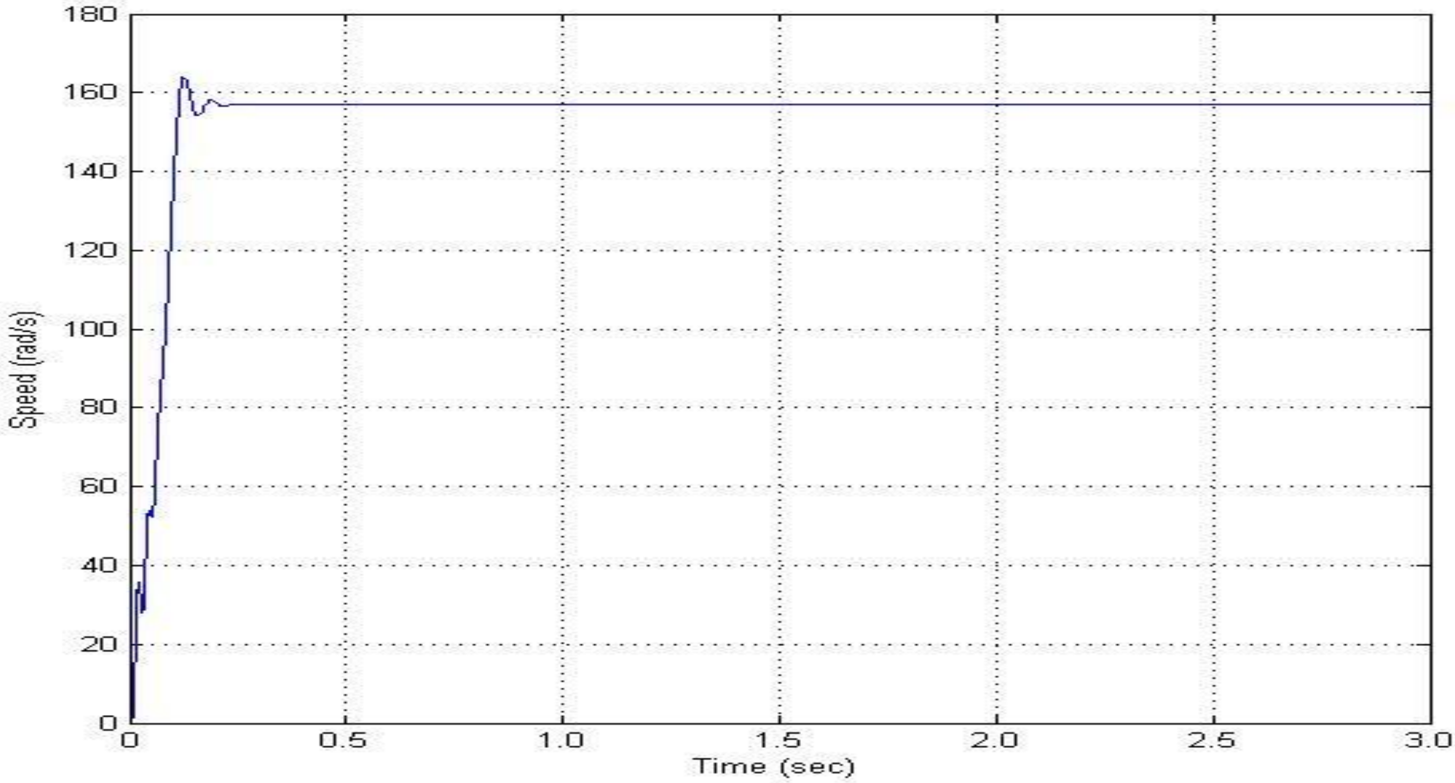

Figure 3.21: Rotor Speed Vs Time graph for machine parameters as in Fig 3.20

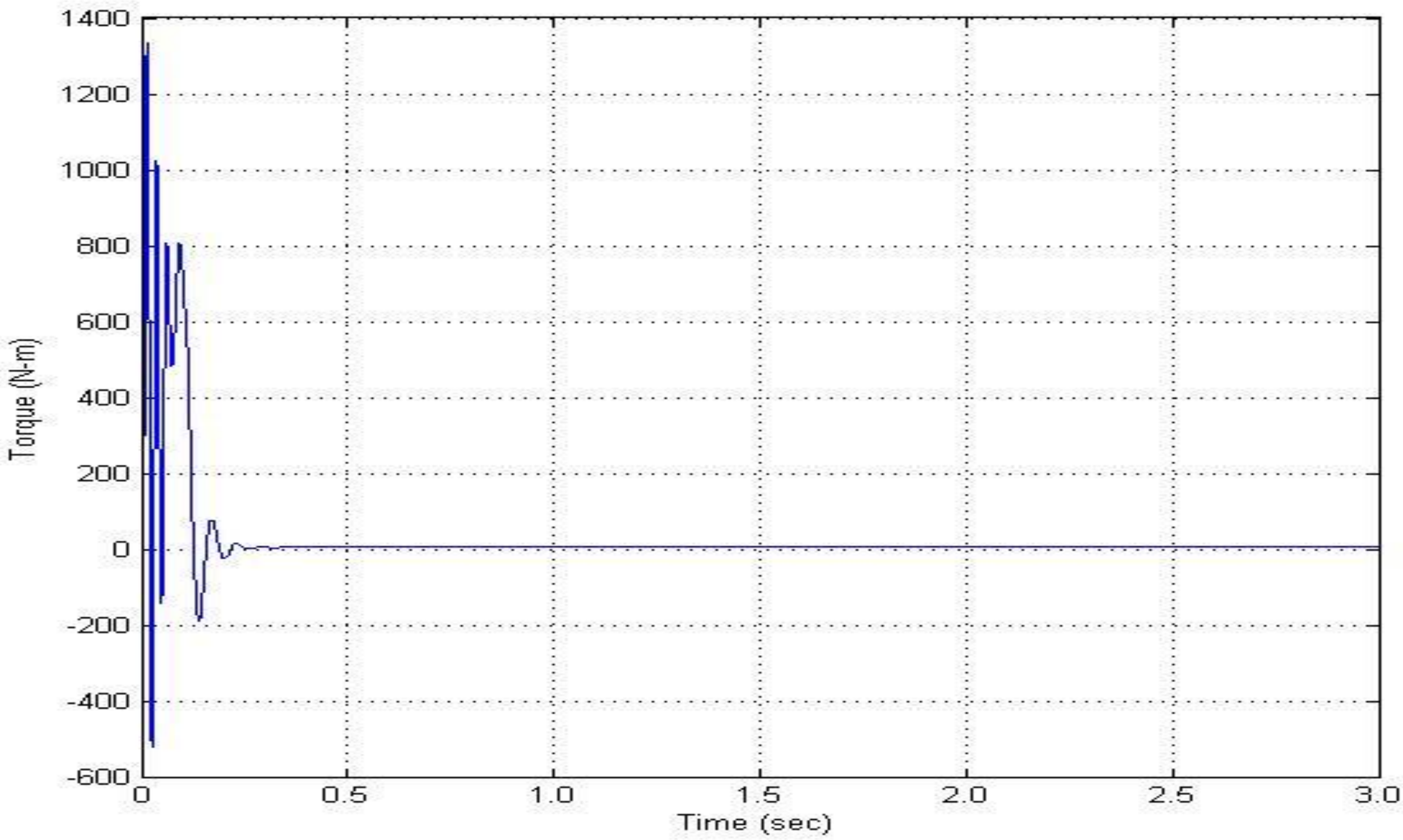

Figure 3.22: Torque Vs Time graph for machine parameters as in Figure 3.20

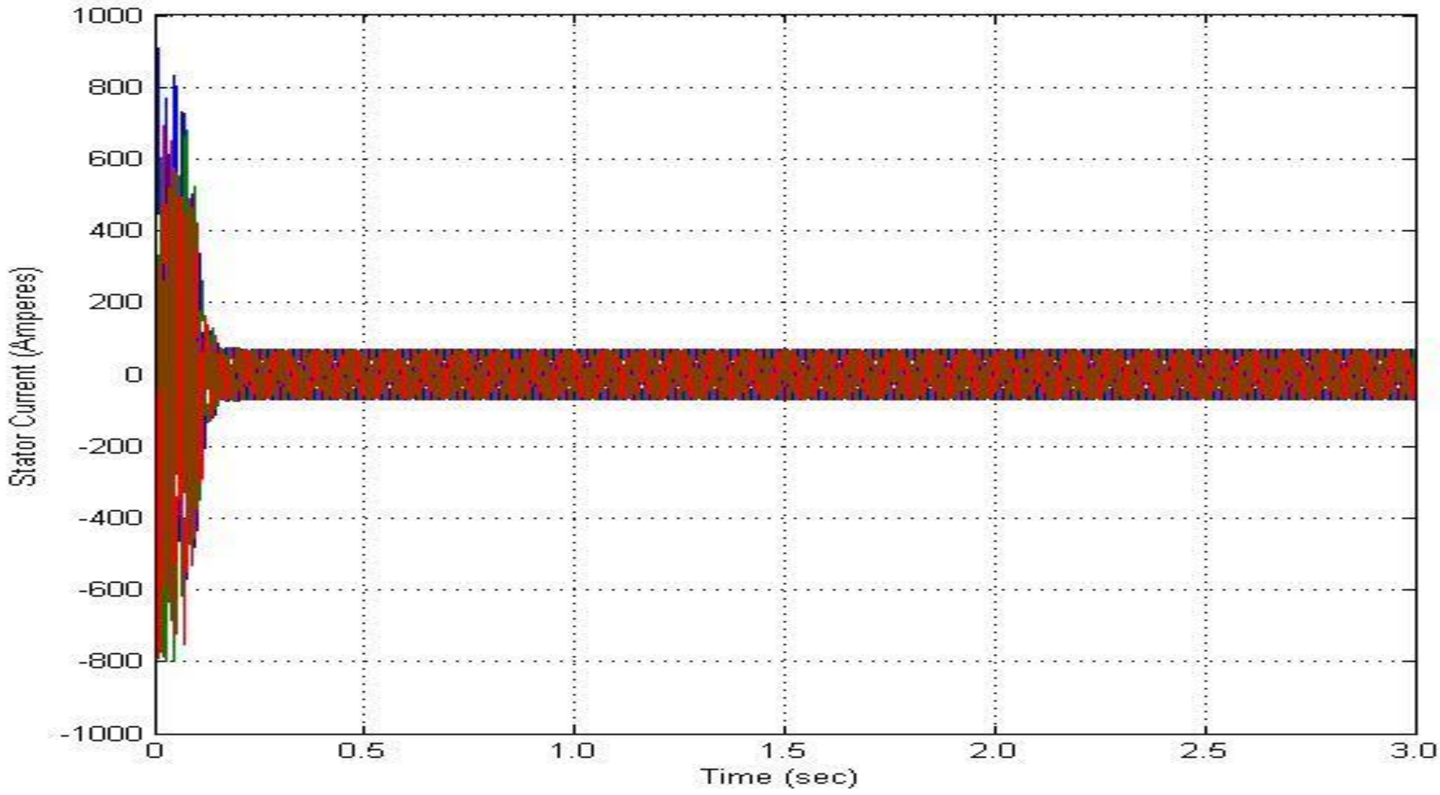

Figure 3.23:Stator Current Vs Time graph for machine parameters as in Fig 3.20

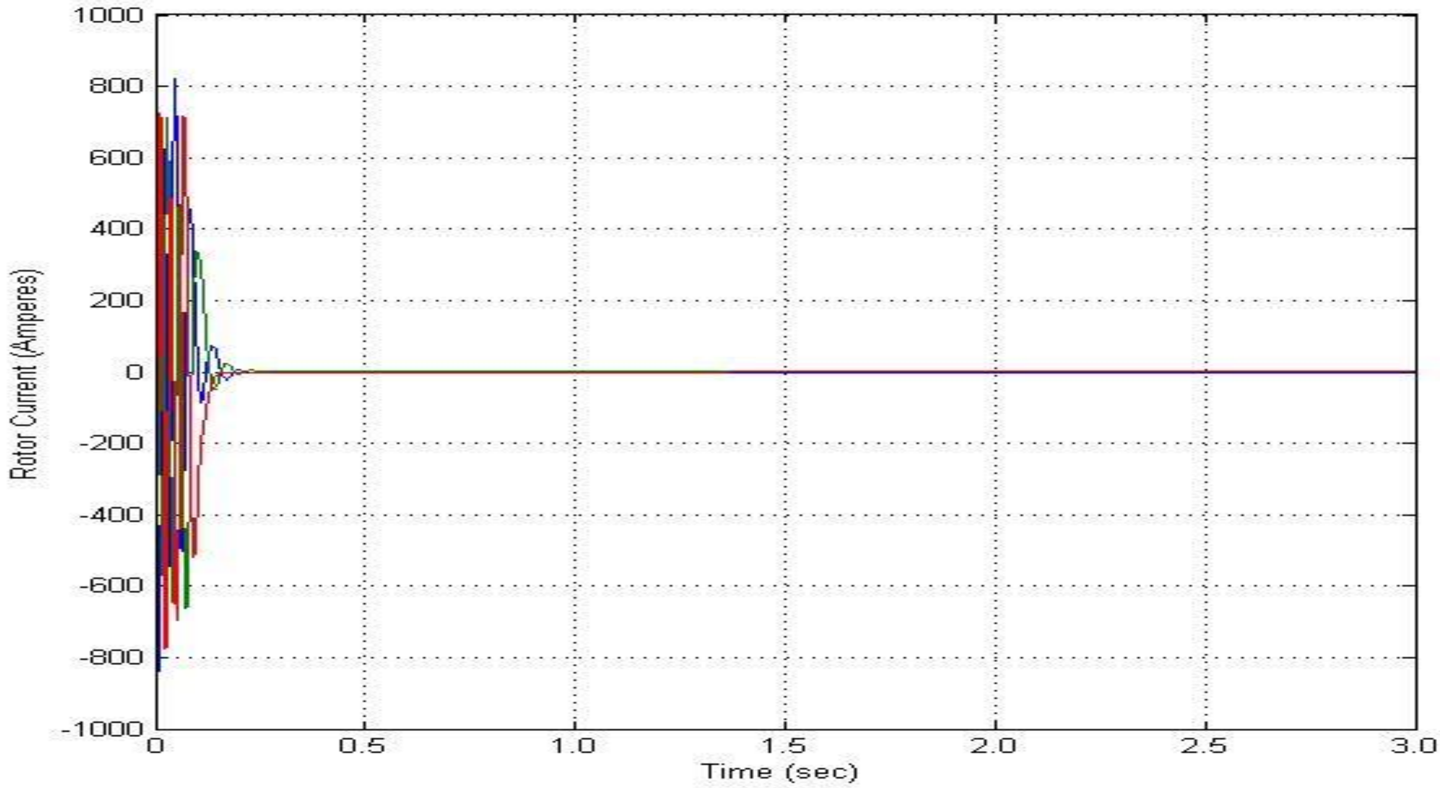

Figure 3.24:Rotor Current Vs Time graph for machine parameters as in Fig 3.20

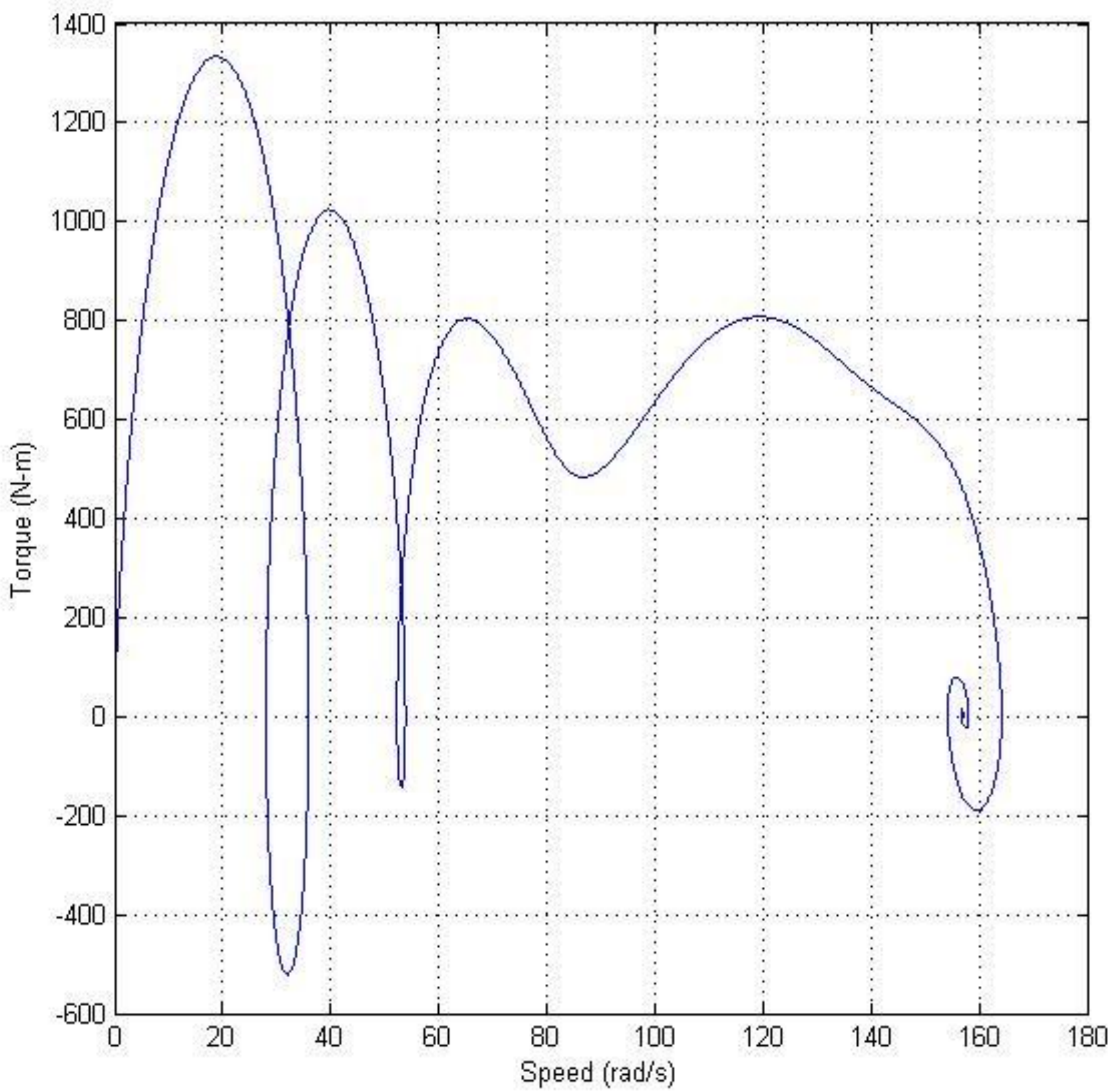

Figure 3.25:Torque-Speed Characteristics for machine parameters as in Fig 3.20

3.5 High Rotor Resistance (~0.5 Ω)

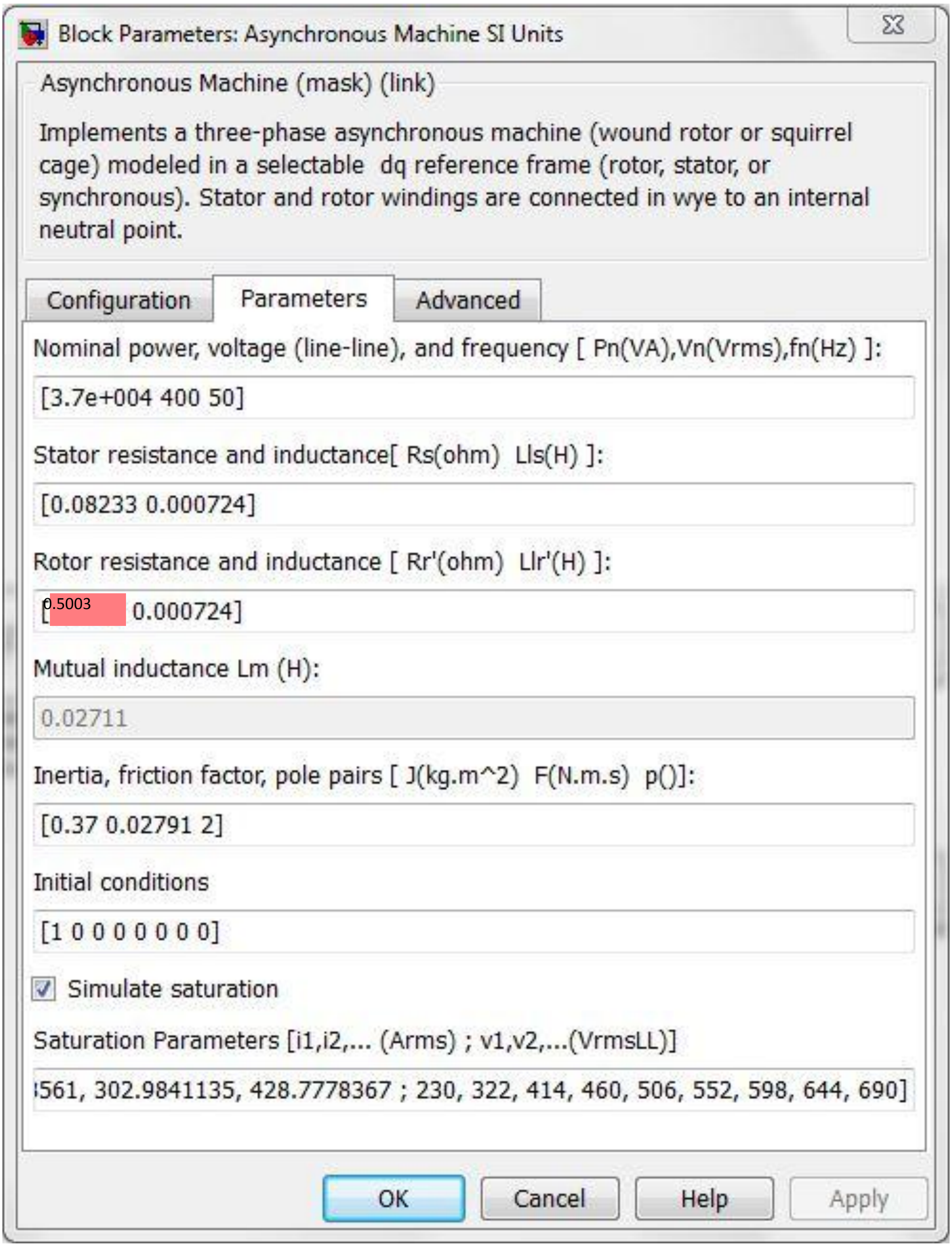

Figure 3.26: Parameters of 3-ϕ induction motors (High Rotor Resistance)

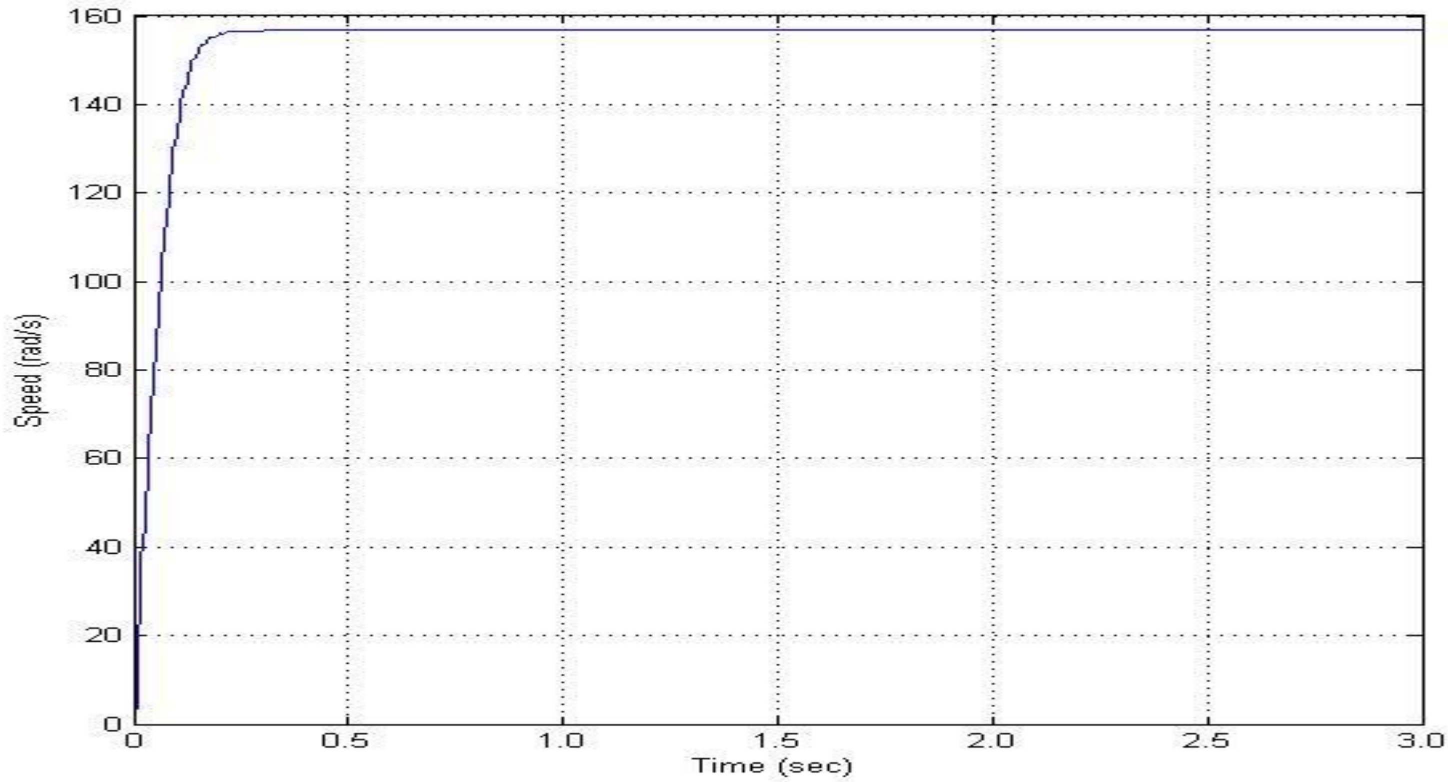

Figure 3.27: Rotor Speed Vs Time graph for machine parameters as in Fig 3.26

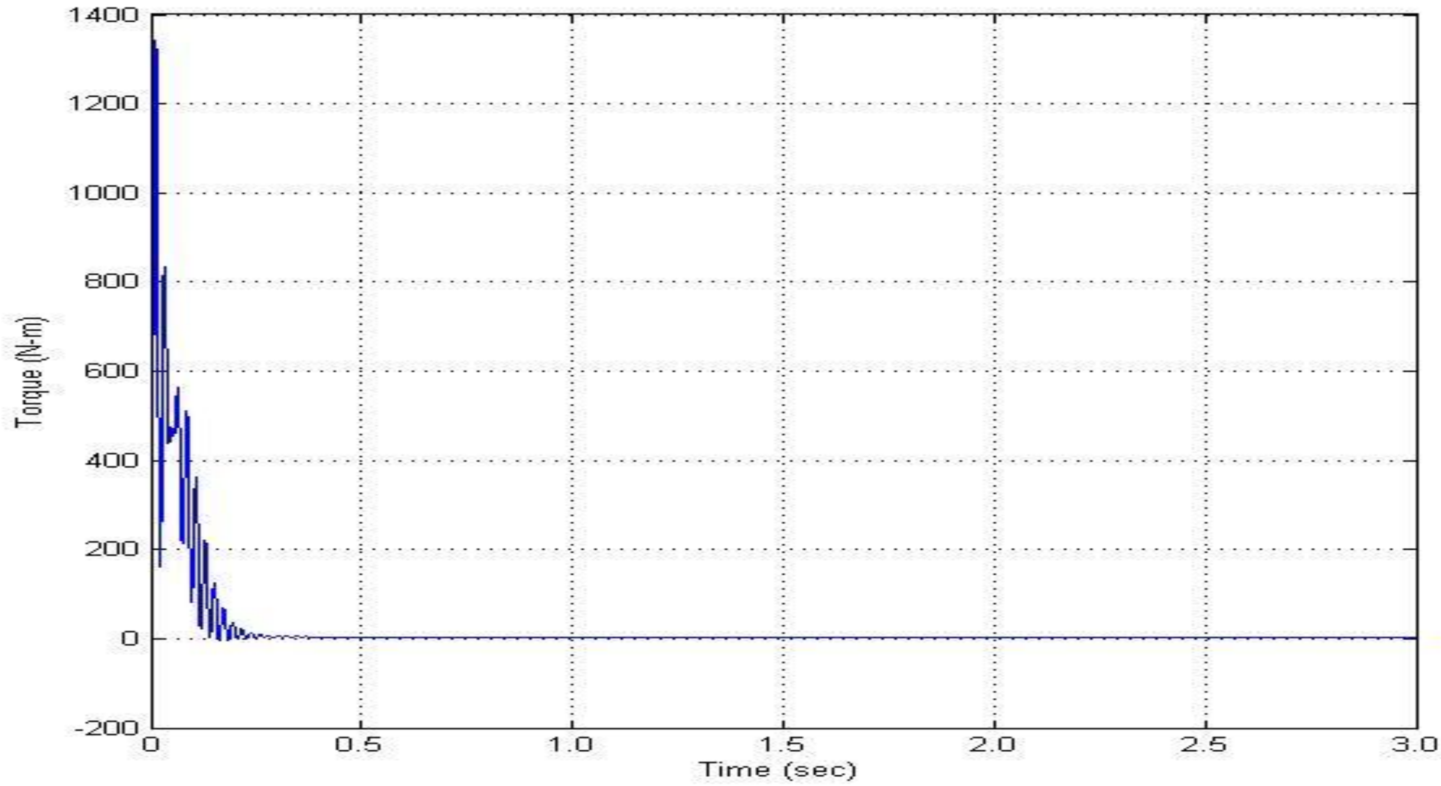

Figure 3.28: Torque Vs Time graph for machine parameters as in Figure 3.26

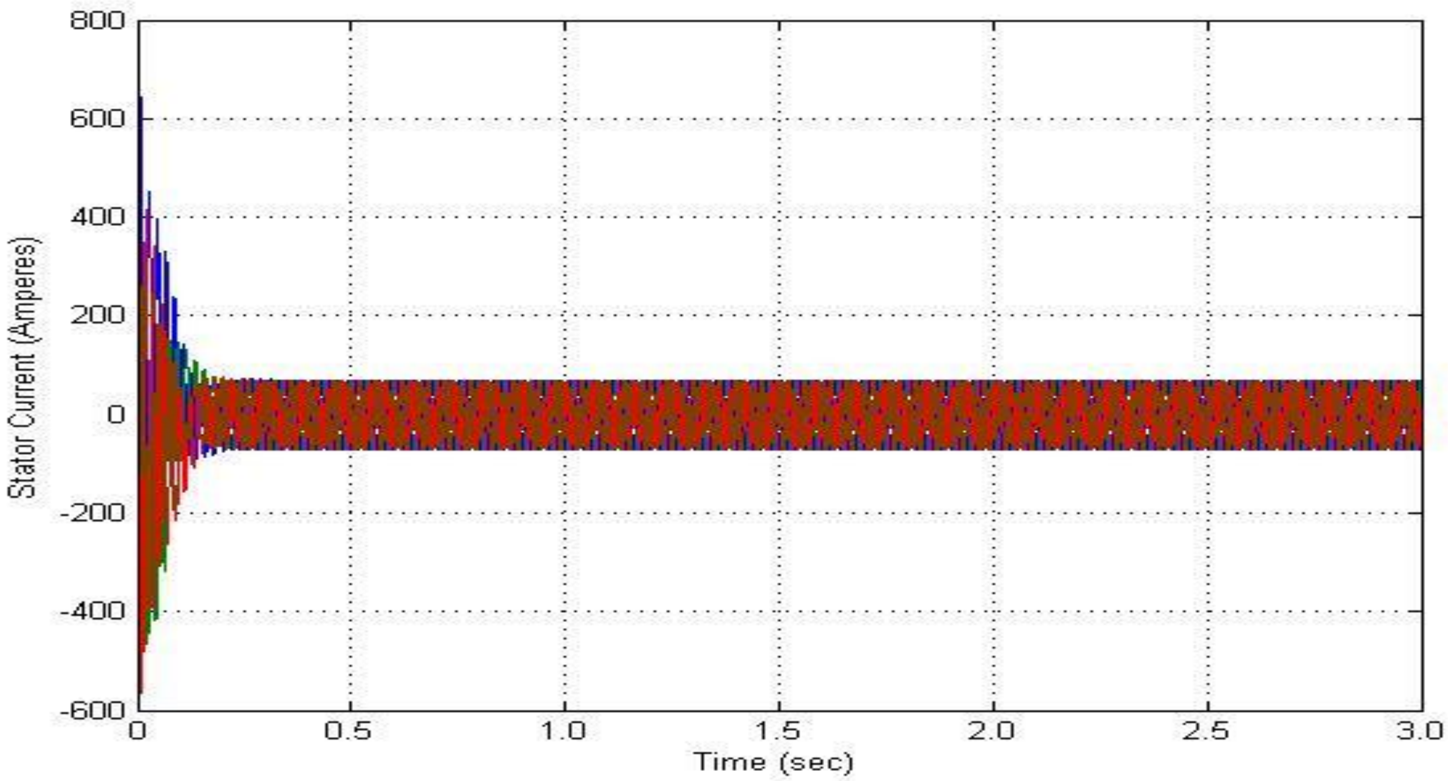

Figure 3.29:Stator Current Vs Time graph for machine parameters as in Fig 3.26

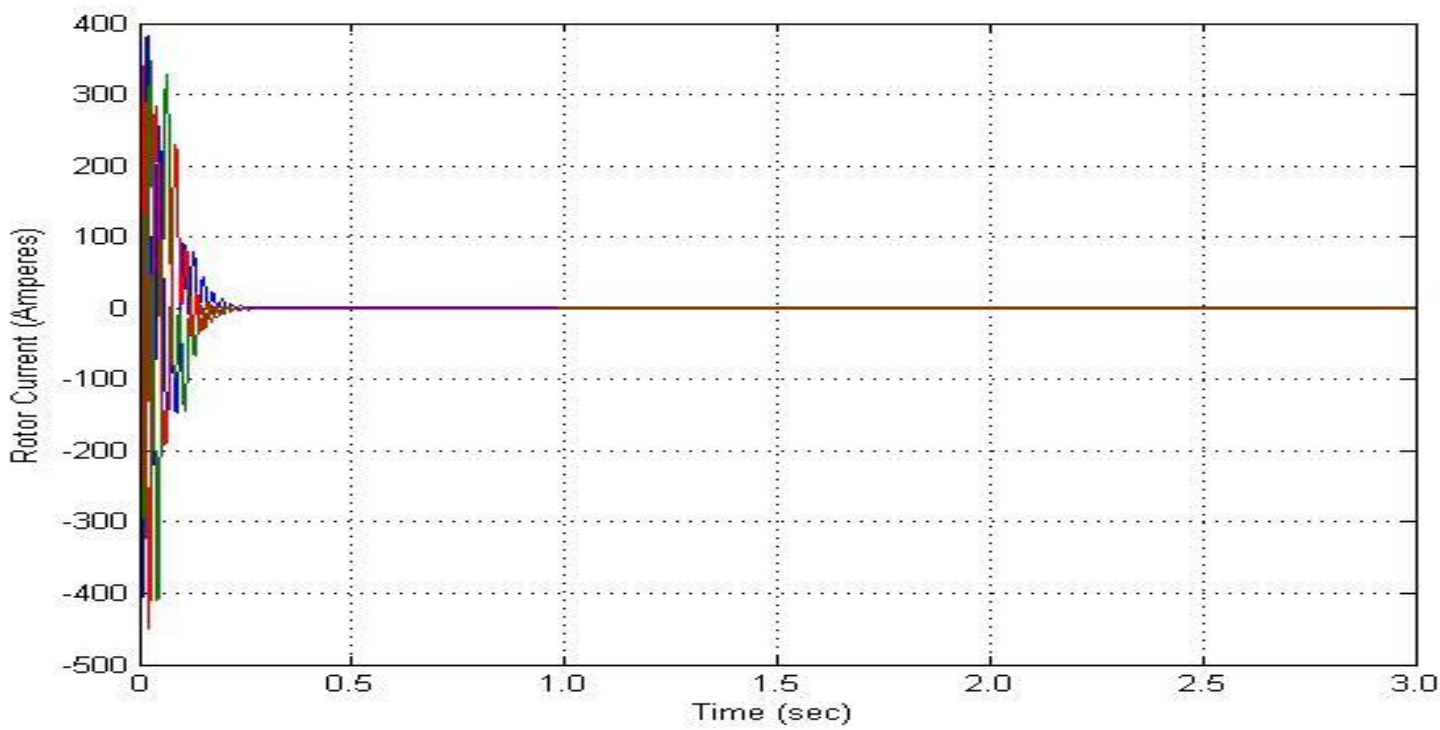

Figure 3.30:Rotor Current Vs Time graph for machine parameters as in Fig 3.26

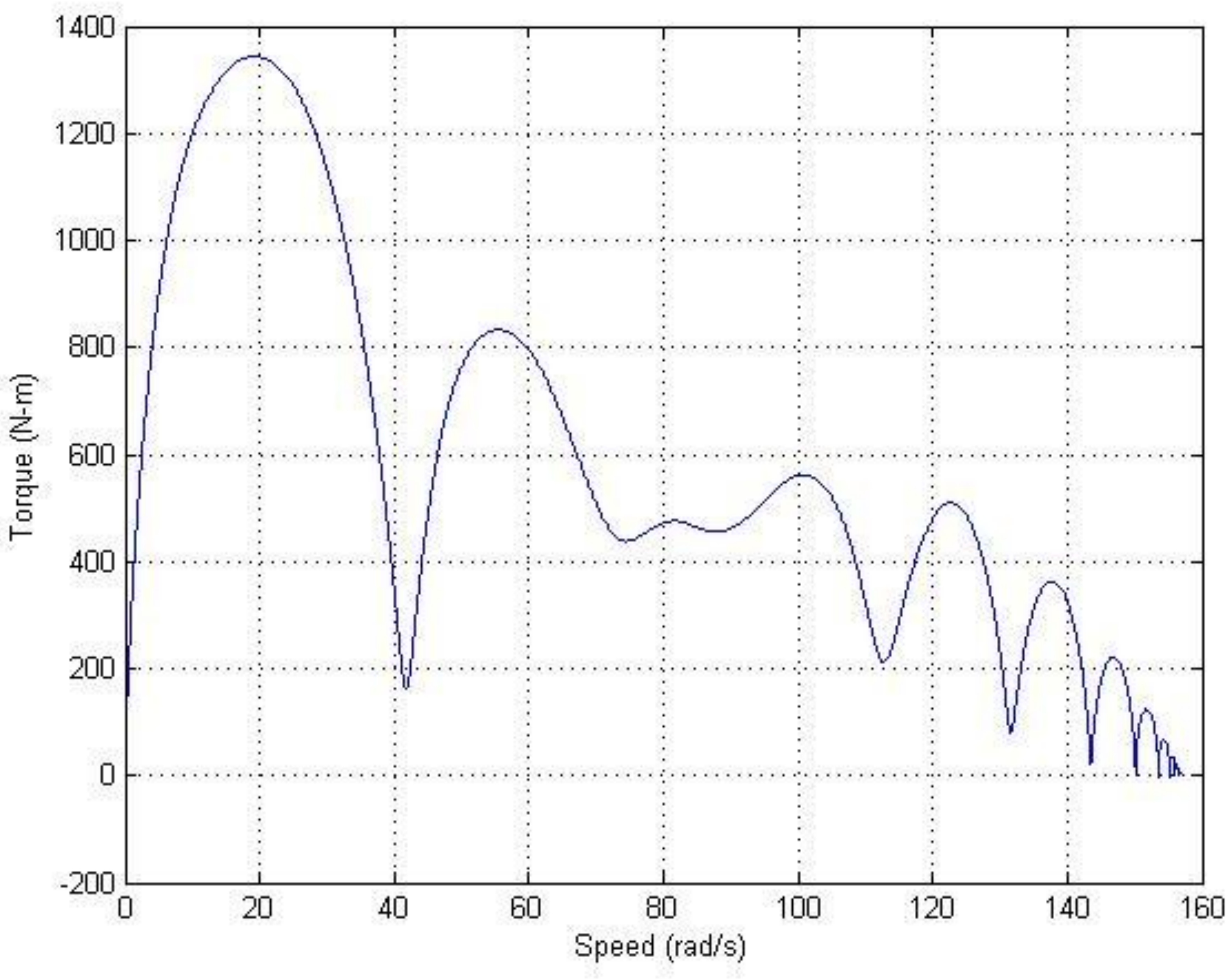

Figure 3.31:Torque-Speed Characteristics for machine parameters as in Fig 3.26

3.6 Low Stator Resistance (~0.16 Ω)

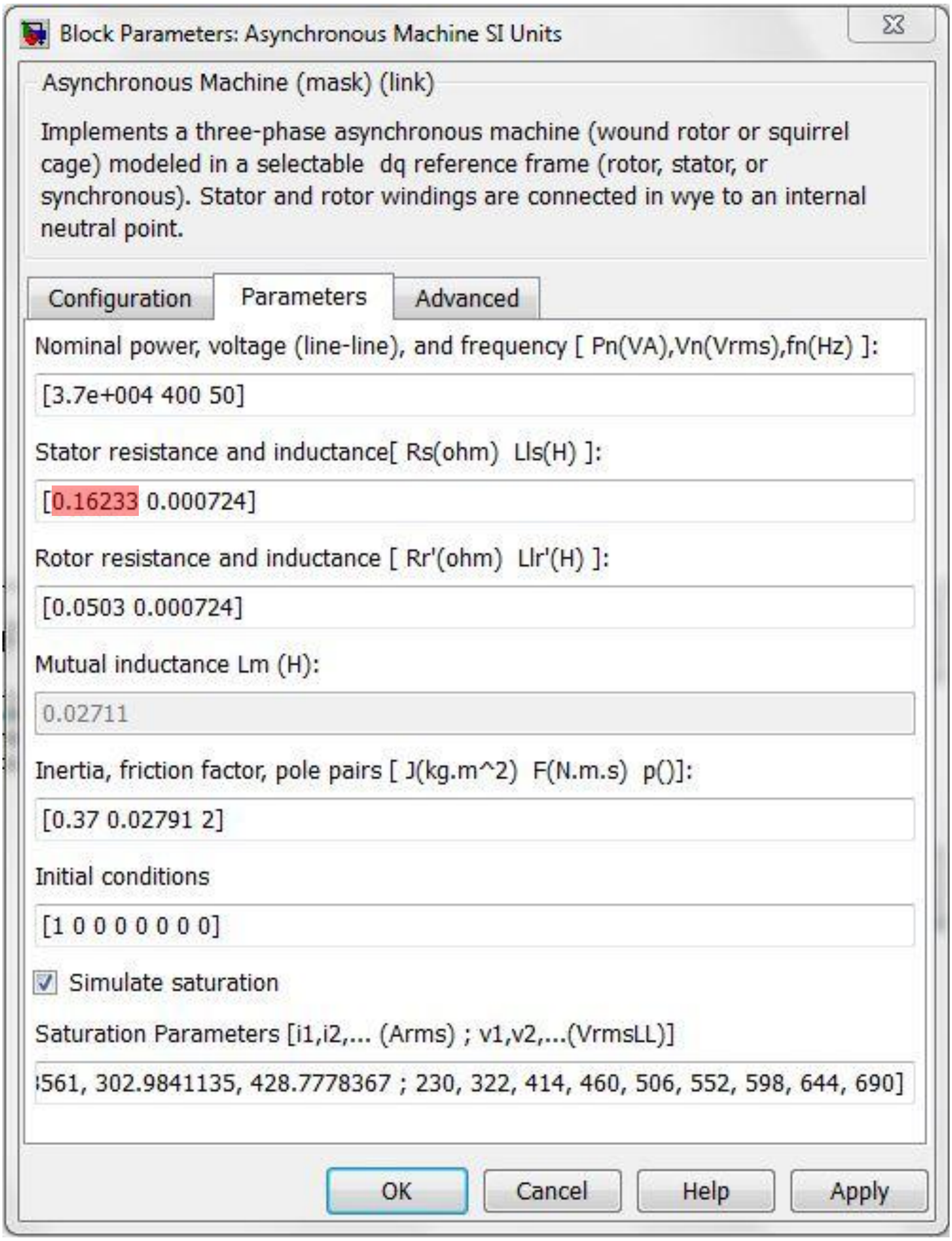

Figure 3.32: Parameters of 3-ϕ induction motors (Low Stator Resistance)

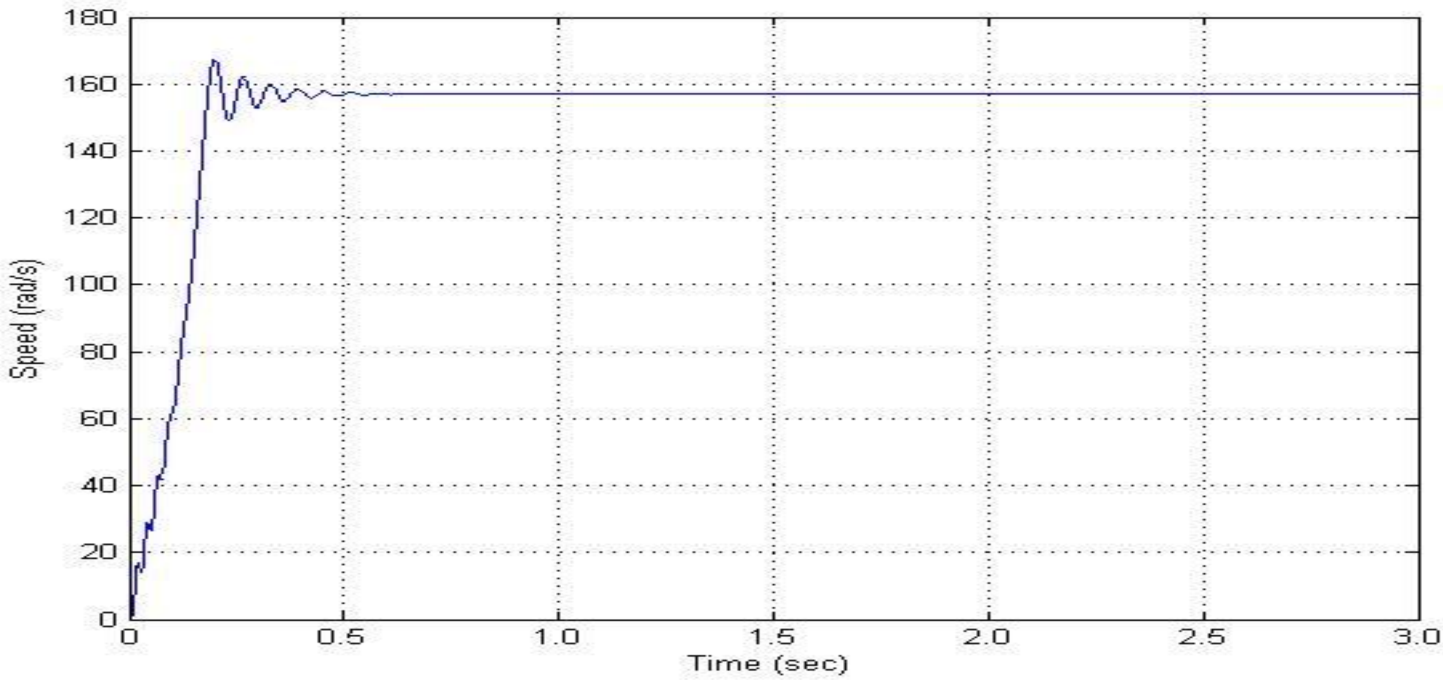

Figure 3.33: Rotor Speed Vs Time graph for machine parameters as in Fig 3.32

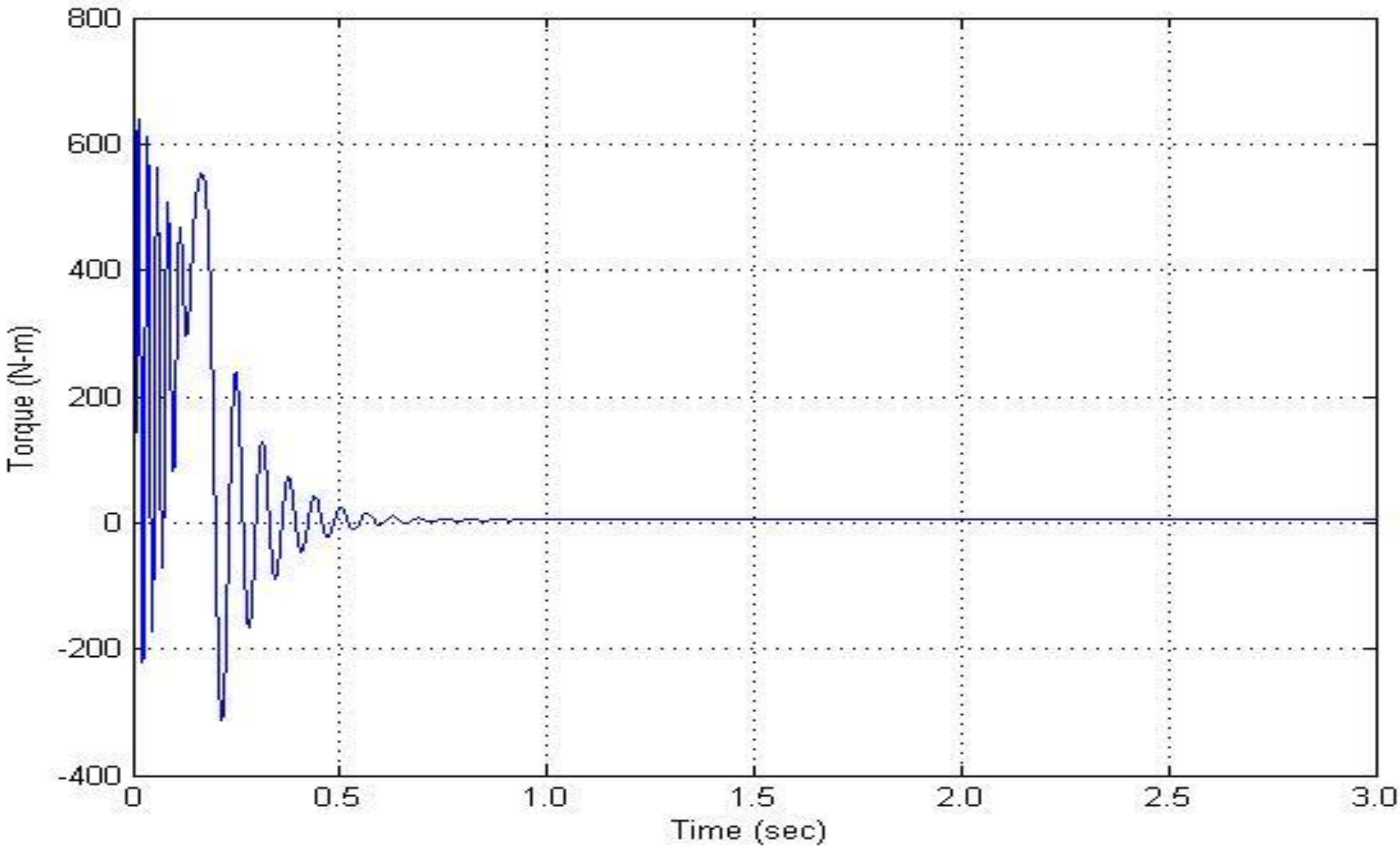

Figure 3.34: Torque Vs Time graph for machine parameters as in Figure 3.32

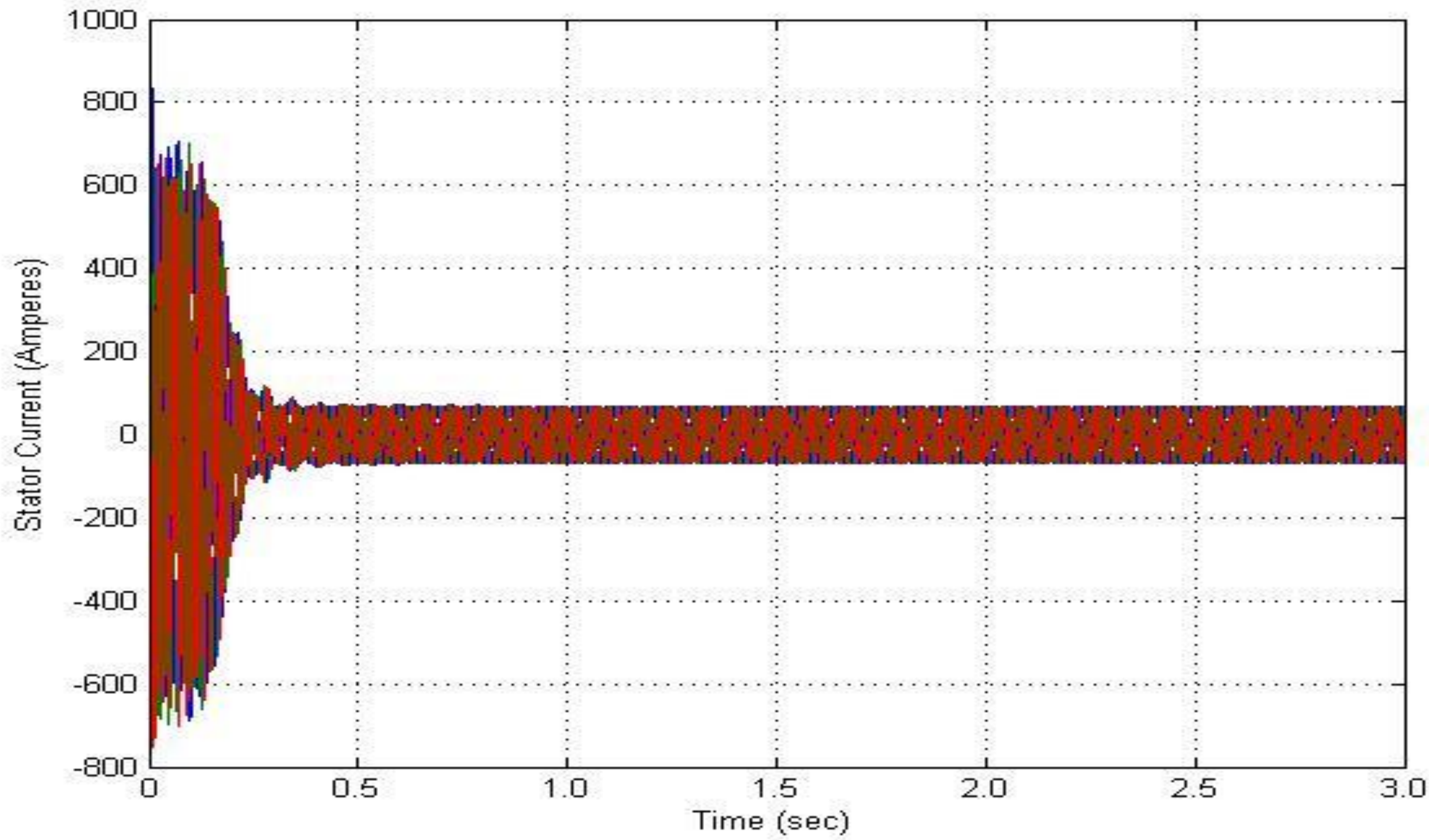

Figure 3.35:Stator Current Vs Time graph for machine parameters as in Fig 3.32

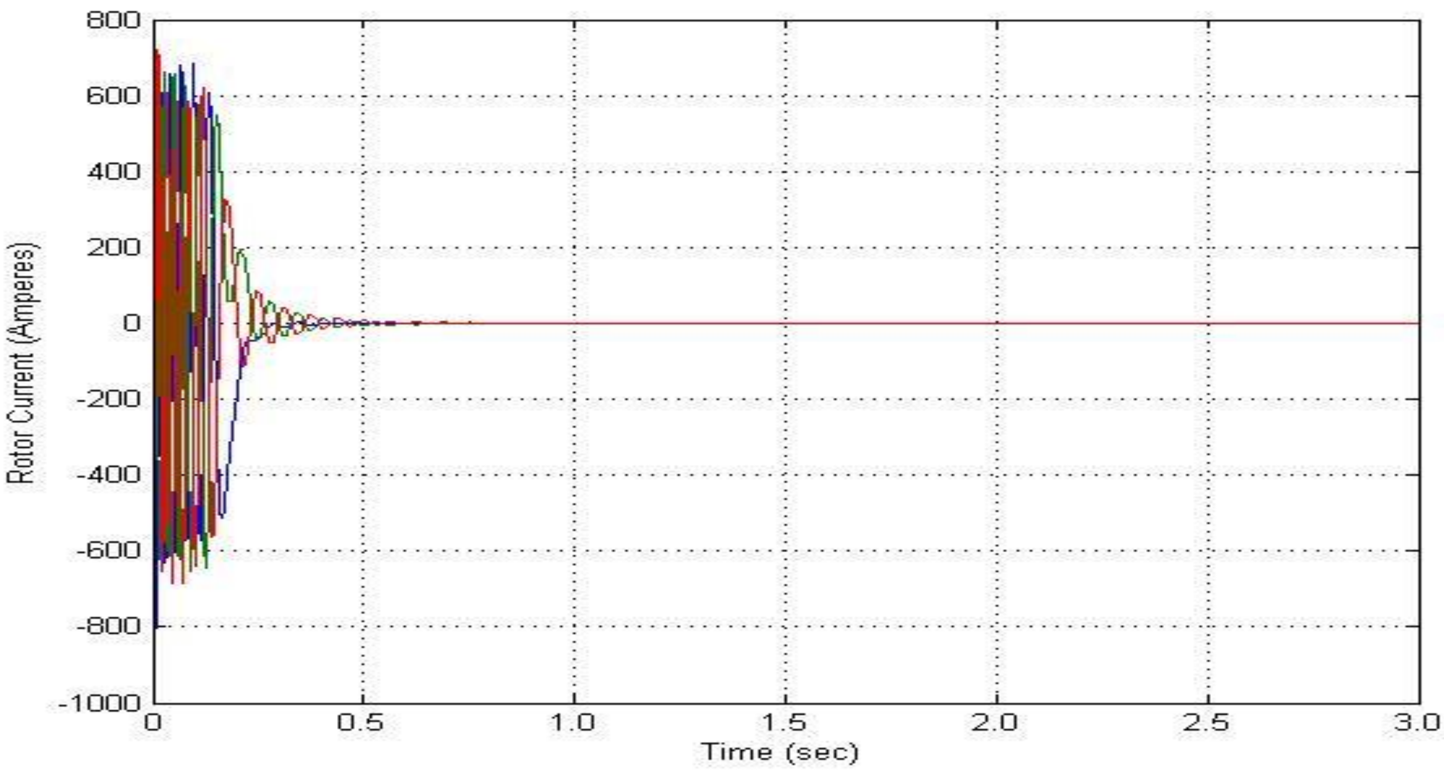

Figure 3.36:Rotor Current Vs Time graph for machine parameters as in Fig 3.32

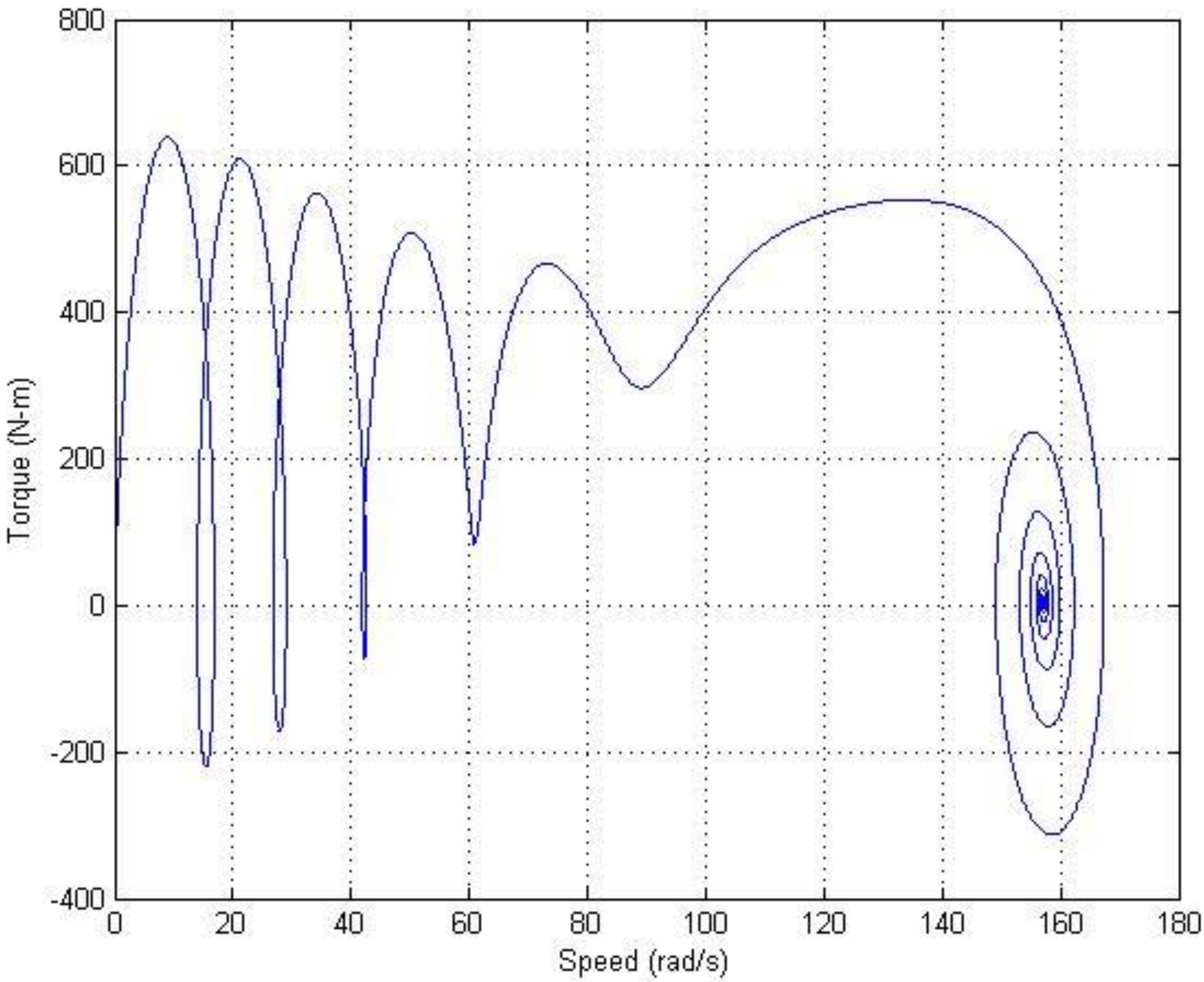

Figure 3.37:Torque-Speed Characteristics for machine parameters as in Fig 3.32

3.7 High Stator Resistance (~0.8 Ω)

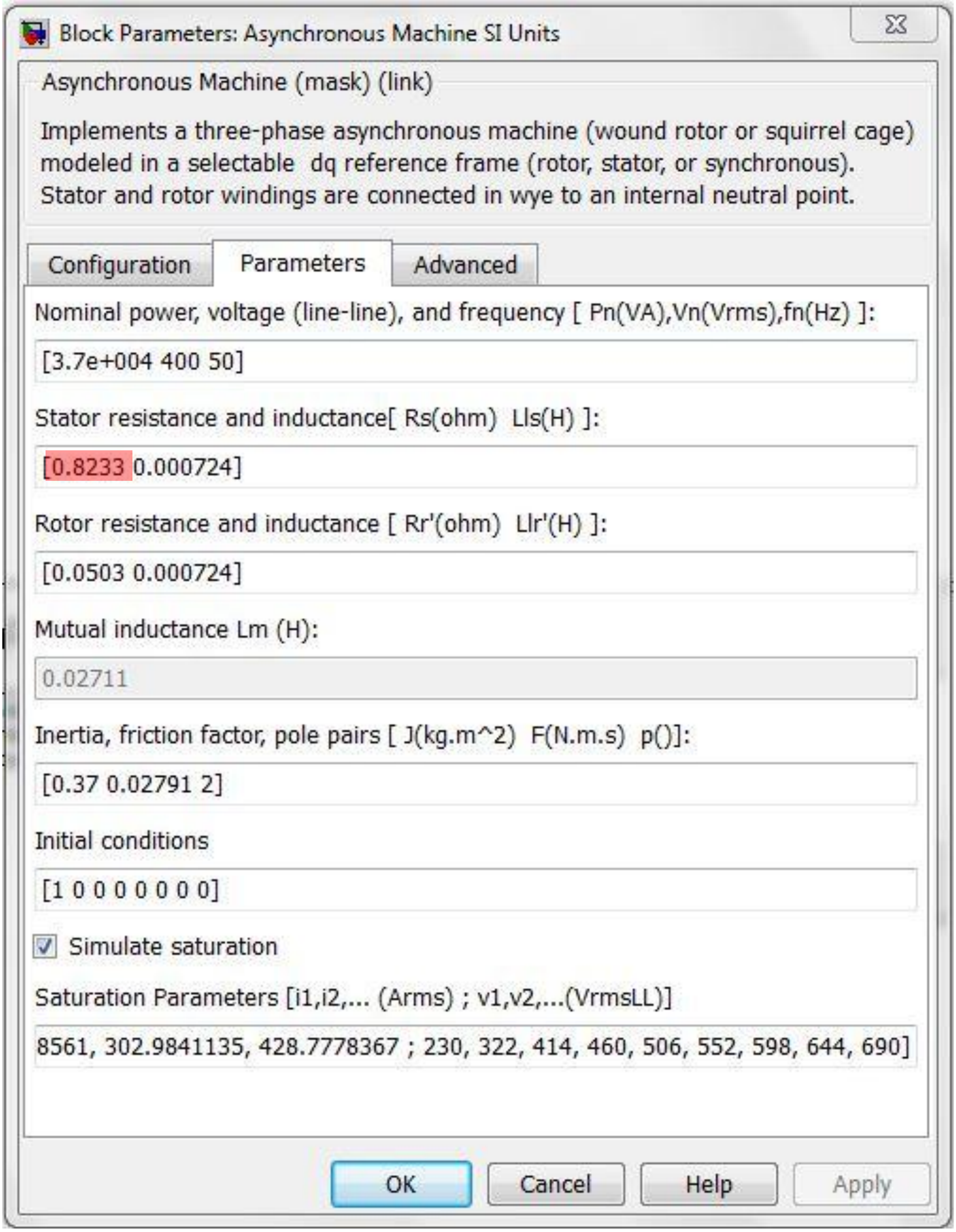

Figure 3.38: Parameters of 3-ϕ induction motors (High Stator Resistance)

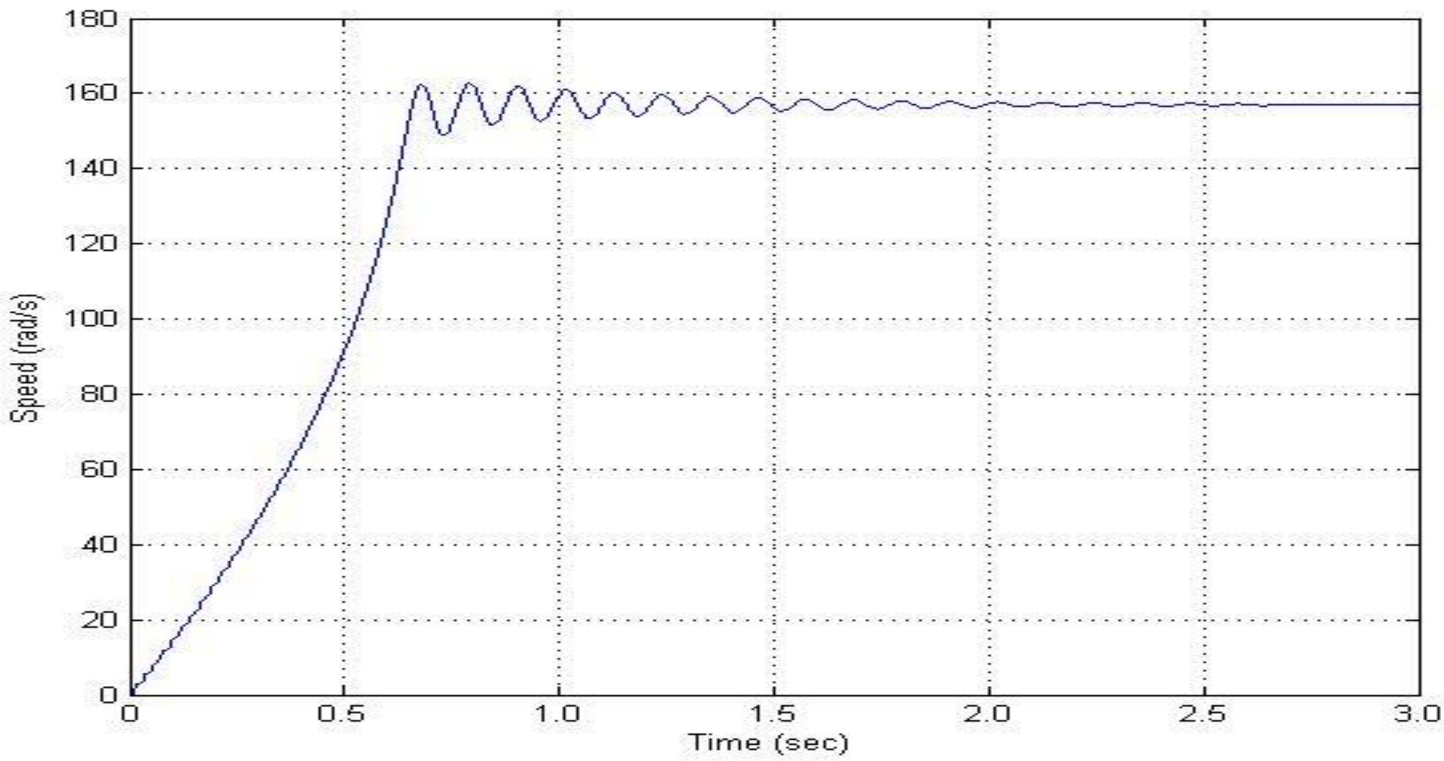

Figure 3.39: Rotor Speed Vs Time graph for machine parameters as in Fig 3.38

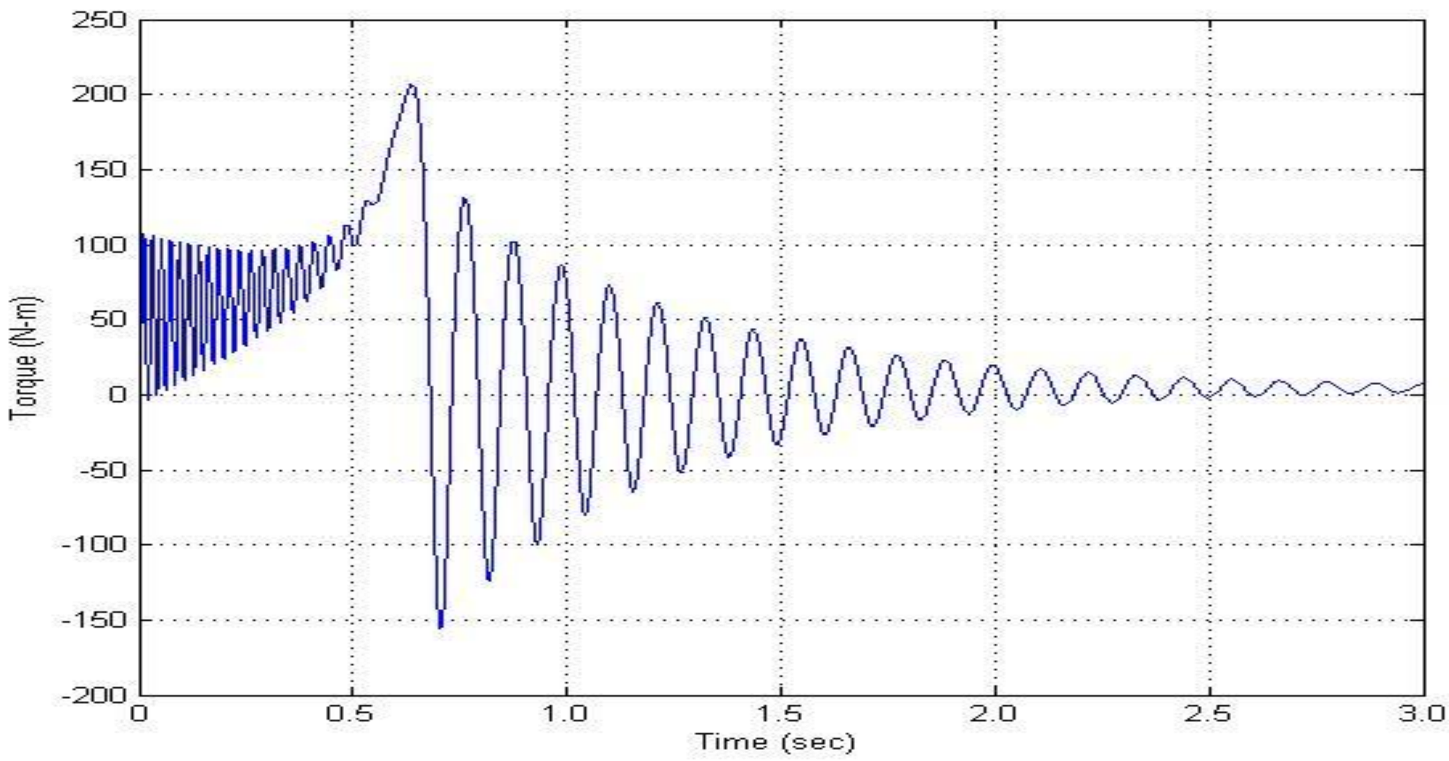

Figure 3.40: Torque Vs Time graph for machine parameters as in Figure 3.38

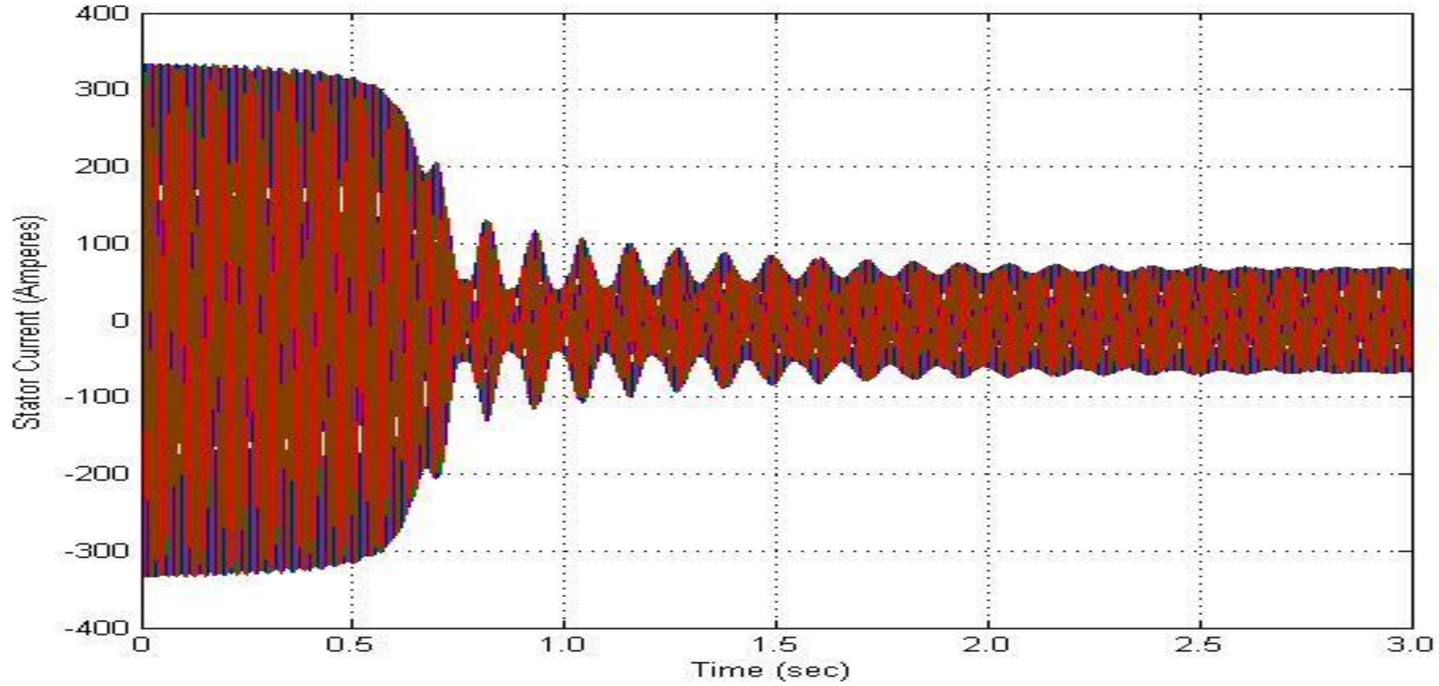

Figure 3.41:Stator Current Vs Time graph for machine parameters as in Fig 3.38

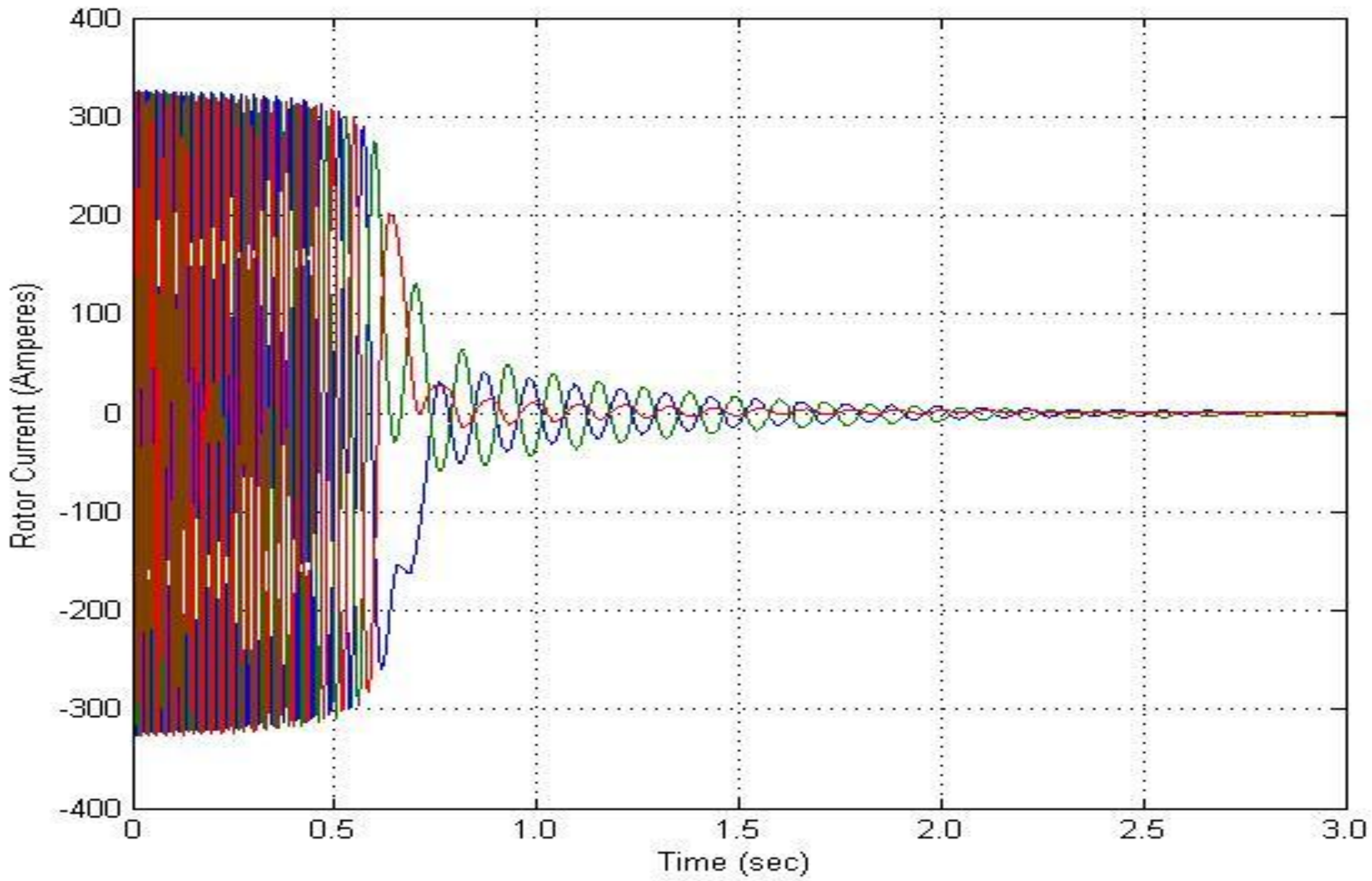

Figure 3.42:Rotor Current Vs Time graph for machine parameters as in Fig 3.38

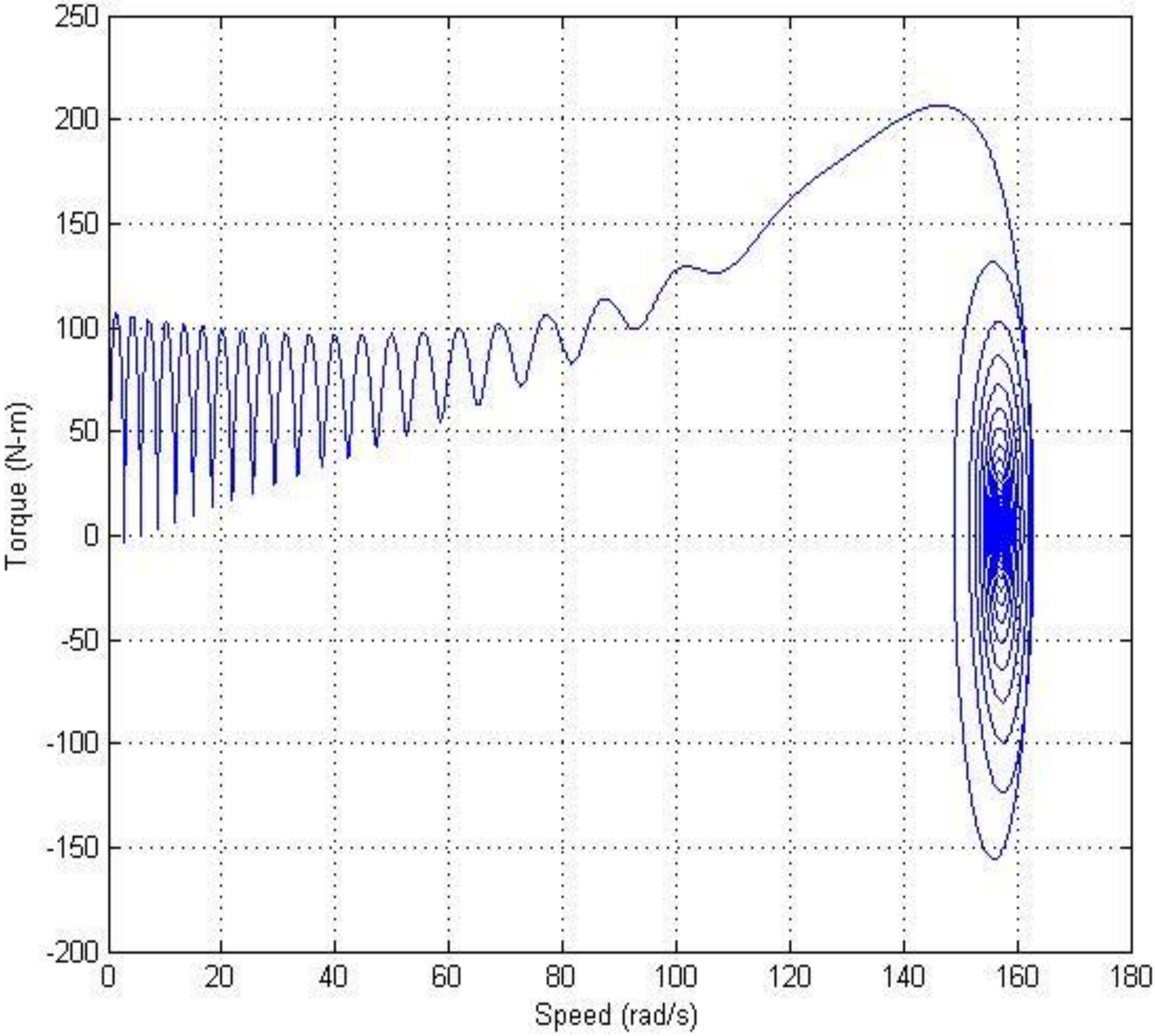

Figure 3.43:Torque-Speed Characteristics for machine parameters as in Fig 3.38

On the basis of the above outcomes, the following observations were made:

i. On increasing the motor inductance (either rotor or stator), the transients lasted for longer period i.e., the machine took longer time to achieve its steady state speed, current and torque. Also the start was a bit jerky.

ii. On increasing the rotor resistance, there was no effect on the steady state time but the machine started with lesser jerks, i.e., the fluctuations in the transient period were reduced. Also the maximum torque occurred at a lower speed.

iii. On increasing the stator resistance, the steady state time increased as well as the machine started with more jerks. Thus the stator resistance must be kept as low as possible.

CHAPTER 4

ANALYSIS OF VARIOUS METHODS FOR SPEED CONTROL OF IM

The various methods of speed control of 3-ϕ Induction motor are as under:

1. Pole Changing
2. Variable Supply Frequency
3. Variable rotor resistance control
4. Variable supply voltage control
5. Constant V/f control
6. Slip recovery
7. Vector Control

However, we shall not be analyzing the pole changing and the variable supply frequency methods as these are very rarely used. This chapter deals with the basic theory behind the several methods of speed control. Hereafter, they are discussed one after the other.

4.1 Variable Rotor Resistance

This method is applicable only to the wound rotor motor as external resistance can be added to it through the slip rings.

A MATLAB code was developed to observe the variation in Torque-Speed characteristics of a 3-ϕ induction motor with variable rotor resistance. The MATLAB code is given in Appendix 1 and the output Torque-Speed characteristics are shown in Figure 4.1 below. The machine details used for the code execution are shown in Table 1 at the end of the chapter.

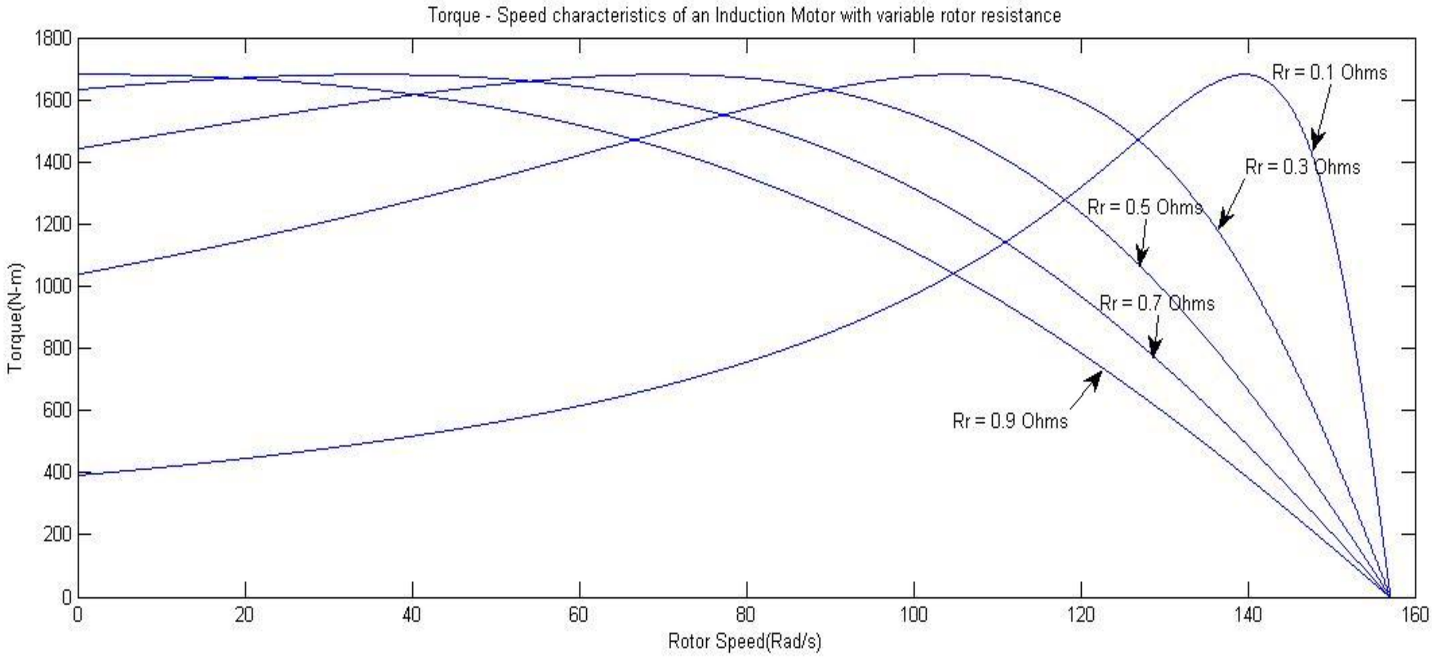

Figure 4.1: Torque-Speed characteristics of a 3-ϕ IM withVariable rotor resistance

External resistances can be connected in the rotor circuit during starting. This increases the starting torque (Equation 2.9 with s=1) and reduces the starting current (Equation 2.3). By making use of appropriate value of resistors, the maximum torque can be made to appear during starting. This can be used in applications requiring high starting torque. Once the motor is started, the external resistance can be cut out to obtain high torque throughout the accelerating range. As external resistances are connected, most of the I^2R loss is dissipated through them thus the rotor temperature rise during starting is limited.

4.2 Variable Stator Voltage

As can be seen from Equation 2.9, the torque developed by an induction motor varies as square of the voltage applied to its stator terminals. Thus by varying the applied voltage, the electromagnetic torque developed by the motor can be varied. This method is generally used for small squirrel-cage motors where cost is an important criterion and efficiency is not. However, this method has rather limited range of speed control.

A MATLAB code was developed to observe the variation in torque-speed characteristics of a 3-ϕ induction motor with variable stator voltage. The MATLAB code is given in Appendix 2 and the output Torque-Speed characteristics are shown in Figure 4.2 below. The machine details used for the code execution are shown in Table 1 at the end of the chapter.

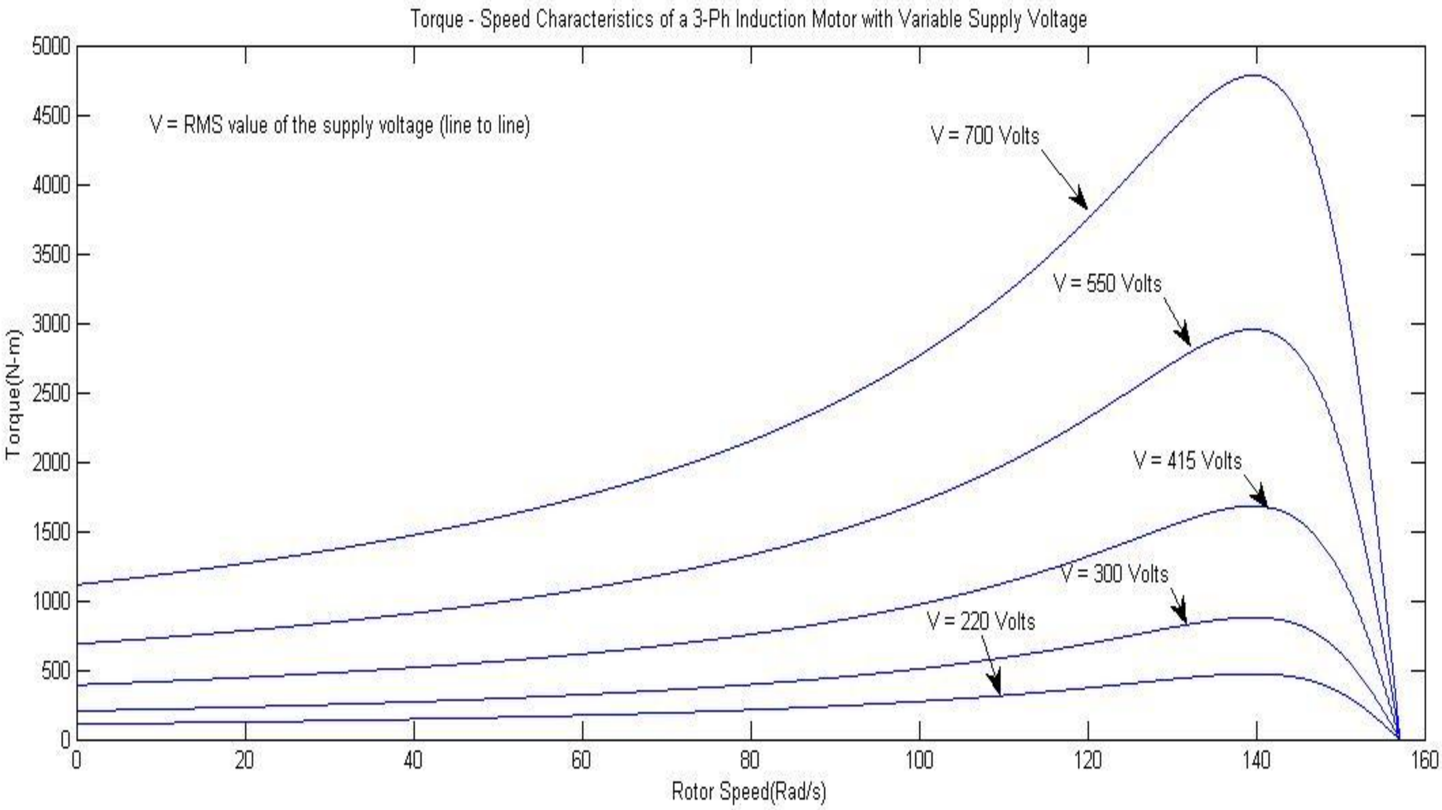

Figure 4.2: Torque-Speed characteristics of a 3-ϕ IM with Variable stator voltage

As the supply voltage is decreased, the value of maximum torque also decreases (Equation 2.11). However it still occurs at the same slip as earlier (Equation 2.10). Even the starting torque and the overall torque reduce (Equation 2.9). Thus the machine is highly underutilized. Thus this method of speed control has very limited applications.

4.3 Constant V/f Control

We vary the stator voltage in such a way that the flux remains constant by simultaneously varying the supply frequency such that the ratio V/f remains constant.

A MATLAB code was developed to observe the variation in torque-speed characteristics of a 3-ϕ induction motor with constant V/f. The MATLAB code is given in Appendix 3 and the output Torque-Speed characteristics are shown in Figure 4.3 below. The machine details used for the code execution are shown in Table 1 at the end of the chapter.

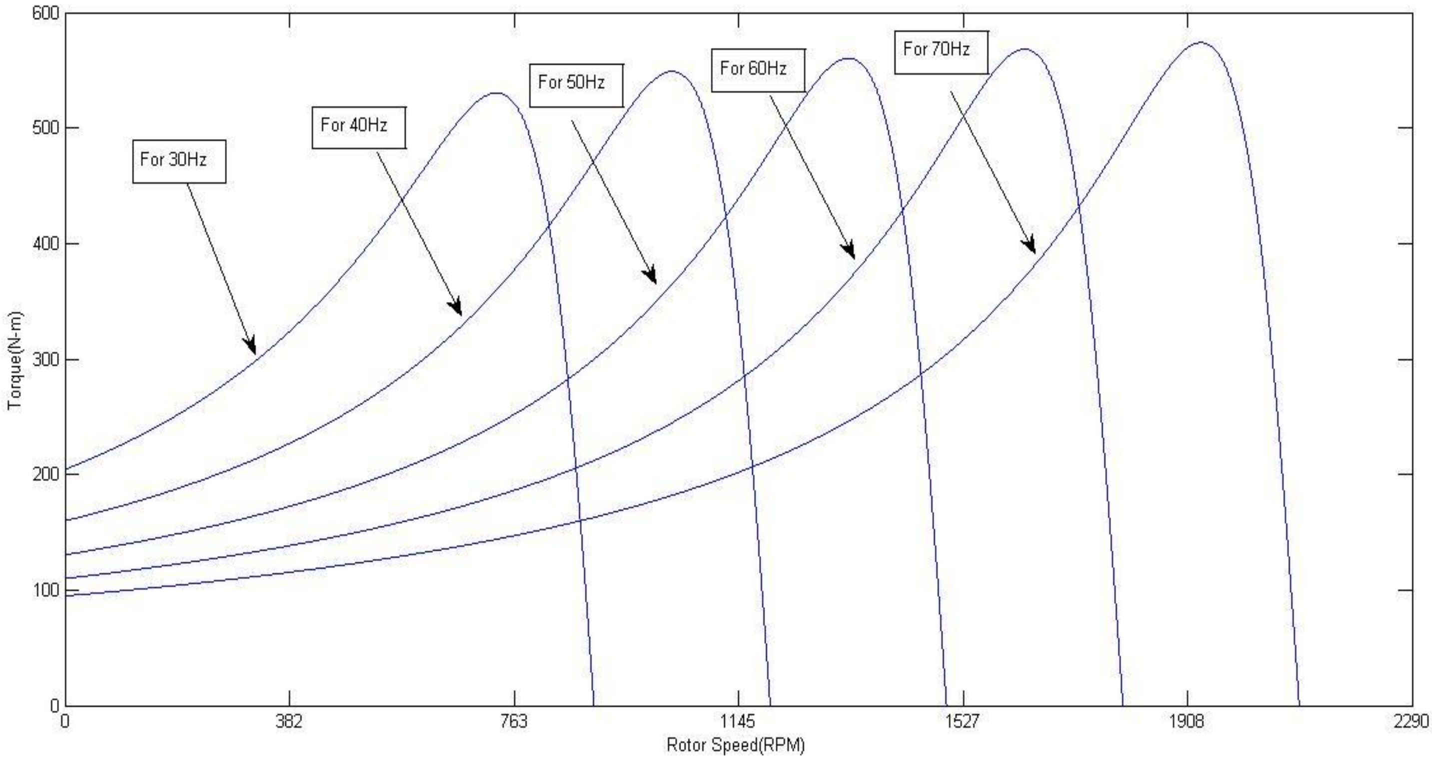

Figure 4.3: Torque-Speed characteristics of a 3-ϕ IM with constant V/f ratio

The AC supply is rectified and then applied to a PWM inverter to obtain a variable frequency, variable magnitude 3-ϕ AC supply.

The electromagnetic torque developed by the motor is directly proportional to the magnetic field produced by the stator and the flux produced by the stator is proportional to the ratio of applied voltage and frequency of supply. Therefore, by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range. This makes constant V/f method the most common speed control method of an induction motor.

4.3.1 Closed Loop V/f speed control method

The basis of constant V/f speed control of induction motor is to apply a variable magnitude and variable frequency voltage to the motor. Both the voltage source inverter and current source inverters are used in adjustable speed ac drives. The following block diagram shows the closed loop V/f control using a VSI.

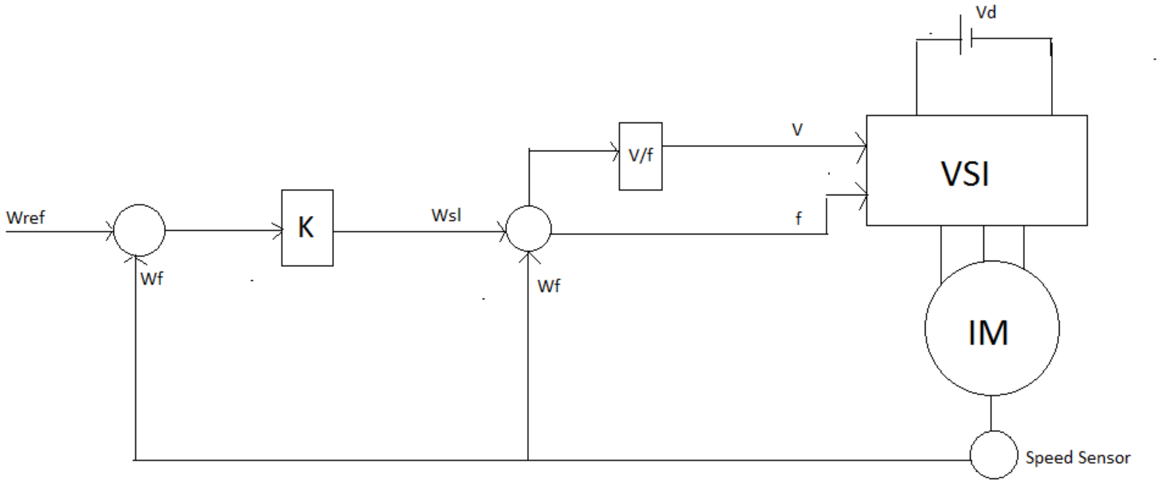

Figure 4.4: Block diagram for closed loop V/f control on a 3-ϕ IM

A speed sensor or a shaft position encoder is used to obtain the actual speed of the motor. It is then compared to a reference speed. The difference between the two generates an error and the error so obtained is processed in a Proportional controller and its output sets the inverter frequency. The synchronous speed, obtained by adding actual speed ωf and the slip speed ω*sl*, determines the inverter frequency. The reference signal for the closed-loop control of the machine terminal voltage V*s* is generated from frequency.

A MATLAB code was developed to observe the variation of frequency as well as the operating zone of the motor with the variation of load torque. Along with the frequency, the voltage was also varied to make V/f ratio constant so that the air gap flux and the maximum torque remain constant. The MATLAB code is given in Appendix 4 and the output Torque-Speed characteristics are shown in Figure 4.5 below. The machine details used for the code execution are shown in Table 1 at the end of the chapter.

```
%Vratedph = Rated Voltage of the motor (per phase) RMS value in Volts
Vratedph=240;

%P = Number of poles
P=4;

%Rs = Stator Resistance in ohms
Rs=0.075;

%Rr = Rotor Resistance in ohms
Rr=0.1;

%Xs = Stator Leakage Reactance @ 50 Hz frequecny in ohms
Xs=0.45;

%Xr = Rotor Leakage Reactance @ 50 Hz frequecny in ohms
Xr=0.45;
```

Figure 4.5: Input Data (Machine details) for Closed loop Constant V/f Speed Control Method

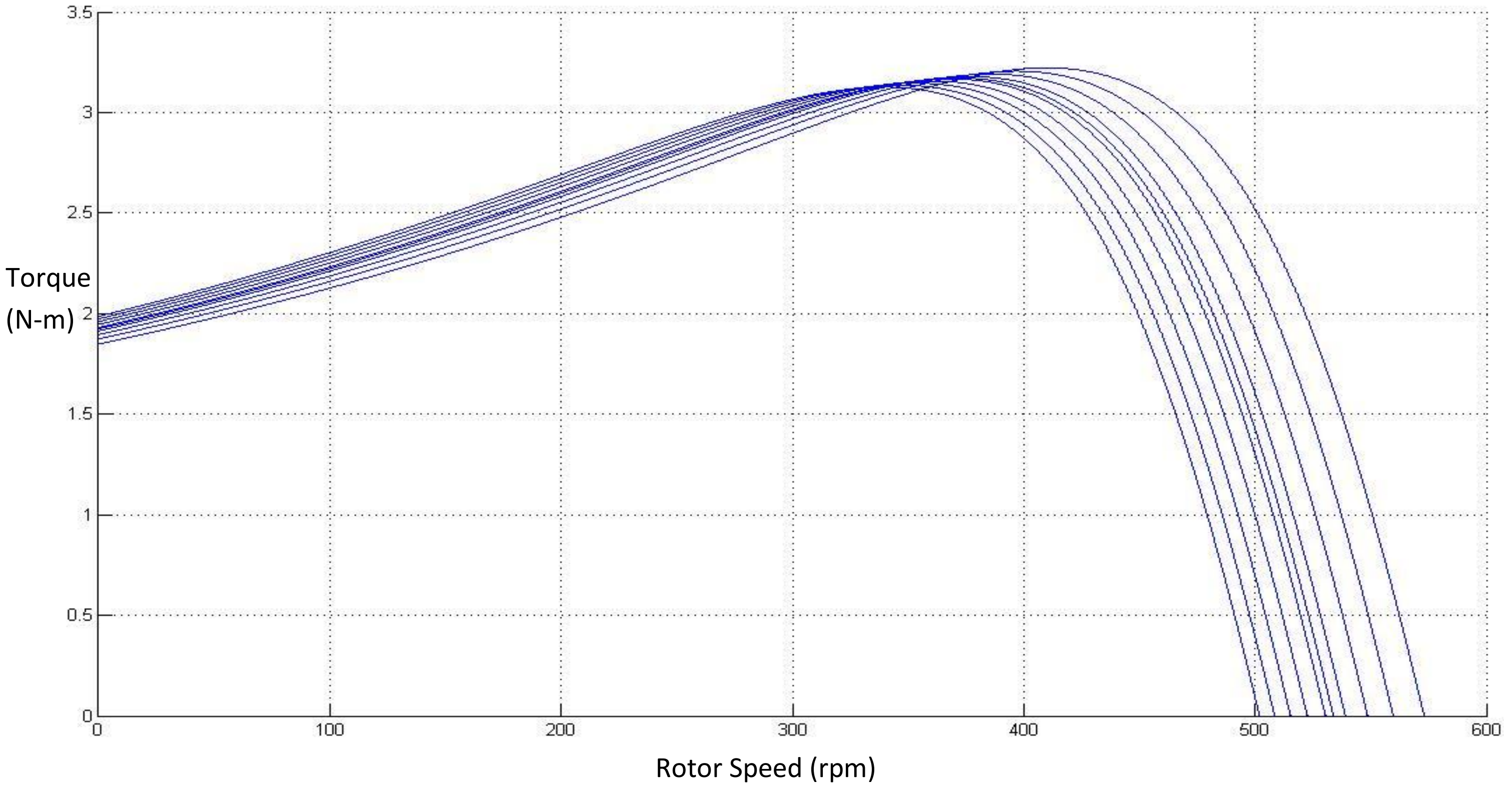

Figure 4.6 Torque-Speed Characteristics with Starting Load Torque 1.5 Nm and Reference Speed 500 rpm

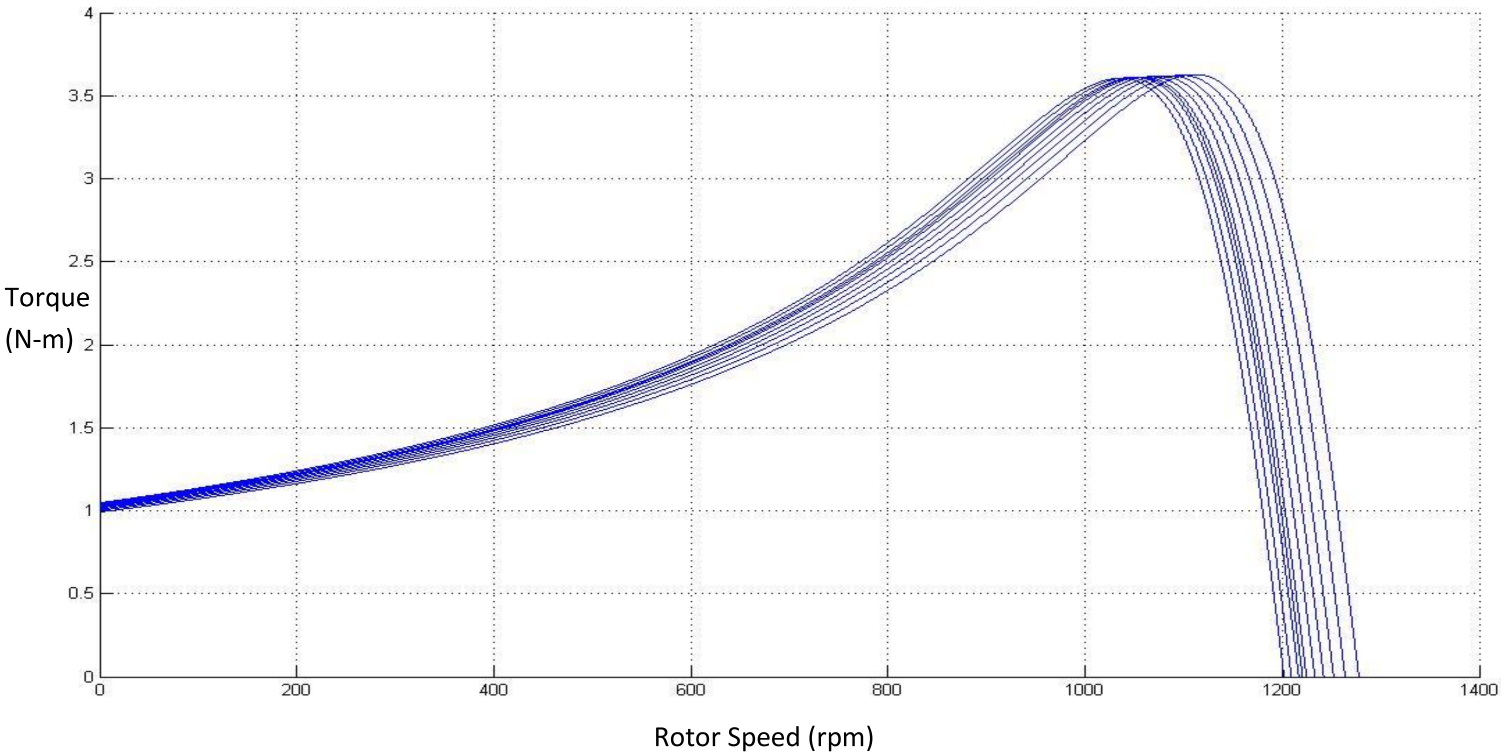

Figure 4.7 Torque-Speed Characteristics with Starting Load Torque 1 Nm and Reference Speed 1200 rpm

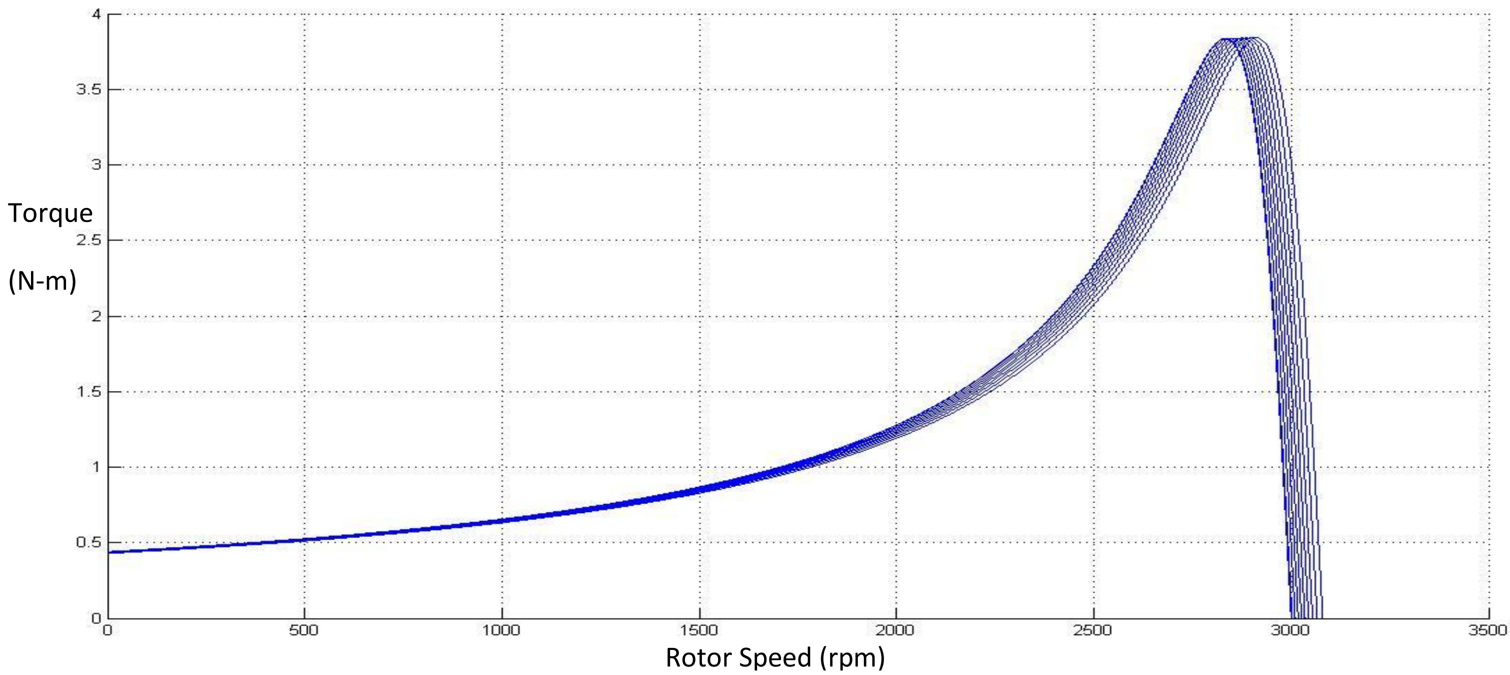

Figure 4.8 Torque-Speed Characteristics with Starting Load Torque 0 Nm and Reference Speed 1500 rpm

Initially the motor was started at a reference speed and a constant load torque. Then the load torque was varied and according to that the speed of operation shifted. The speed was taken as a feedback and the error in the speed was calculated and the frequency was adjusted accordingly by proportional controller. This corrected frequency is given to the voltage source inverter. Simultaneously the voltage is varied such that the V/f ratio remains constant for any value of frequency. Hence we can an approximate constant speed for different loads.

4.3.2 Open Loop V/f speed control method using PI controller

A SIMULINK block was created to analyse the open loop constant V/f control method using PI controller and the Stator current (Figure 4.10), DC voltage (Figure 4.11), Electromagnetic torque (Figure 4.12) and Rotor speed (Figure 4.13) were plotted against time. The SIMULINK block is given below followed by the outcomes.

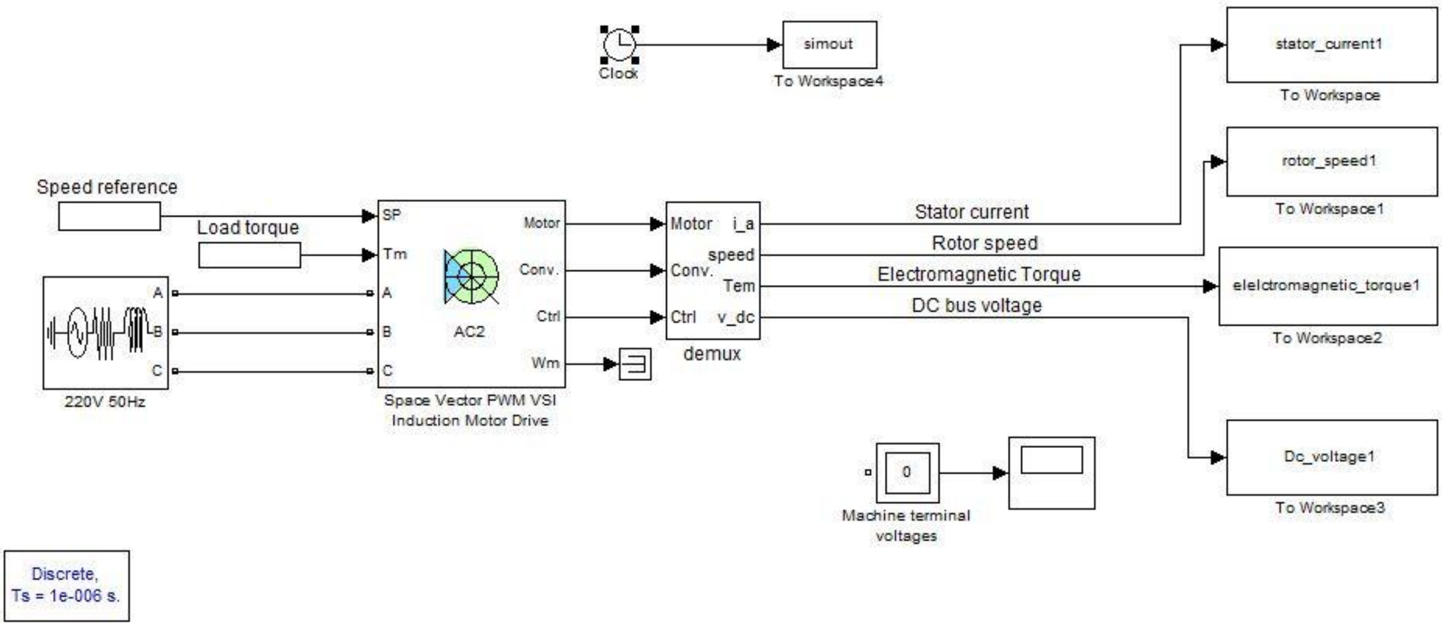

Figure 4.9: SIMULINK block of open loop constant V/f speed control using PI controller

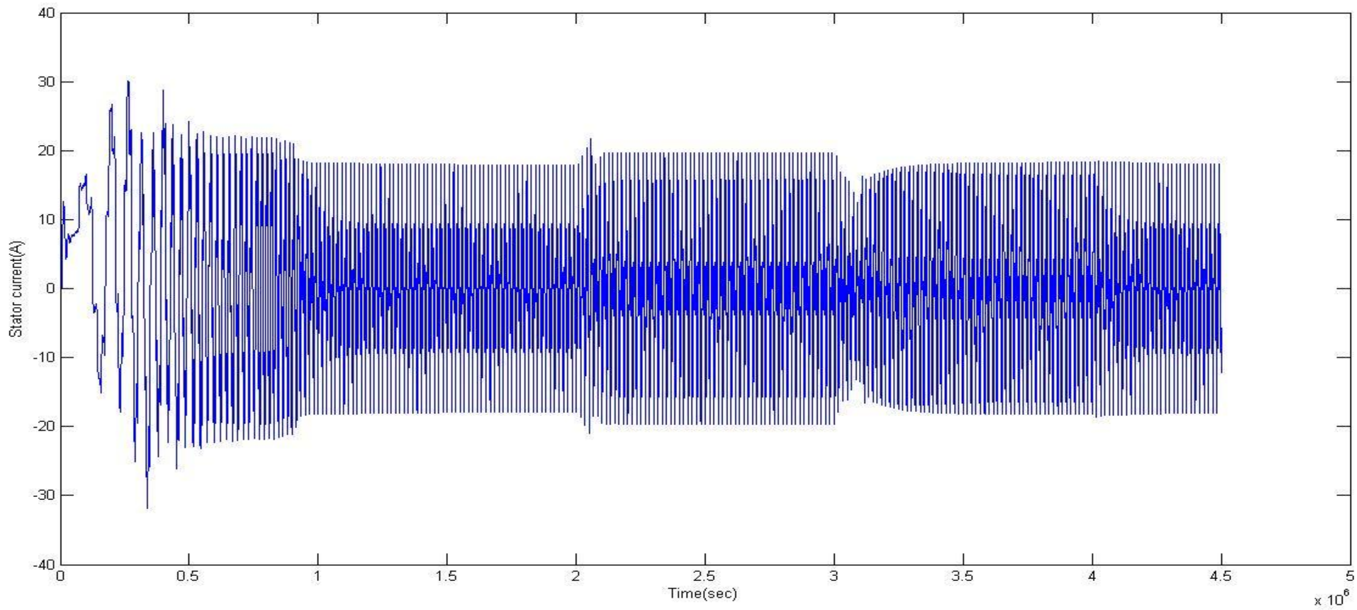

Figure 4.10: Variation of Stator current of a 3-ϕ in case of open loop PI control for constant V/f control method

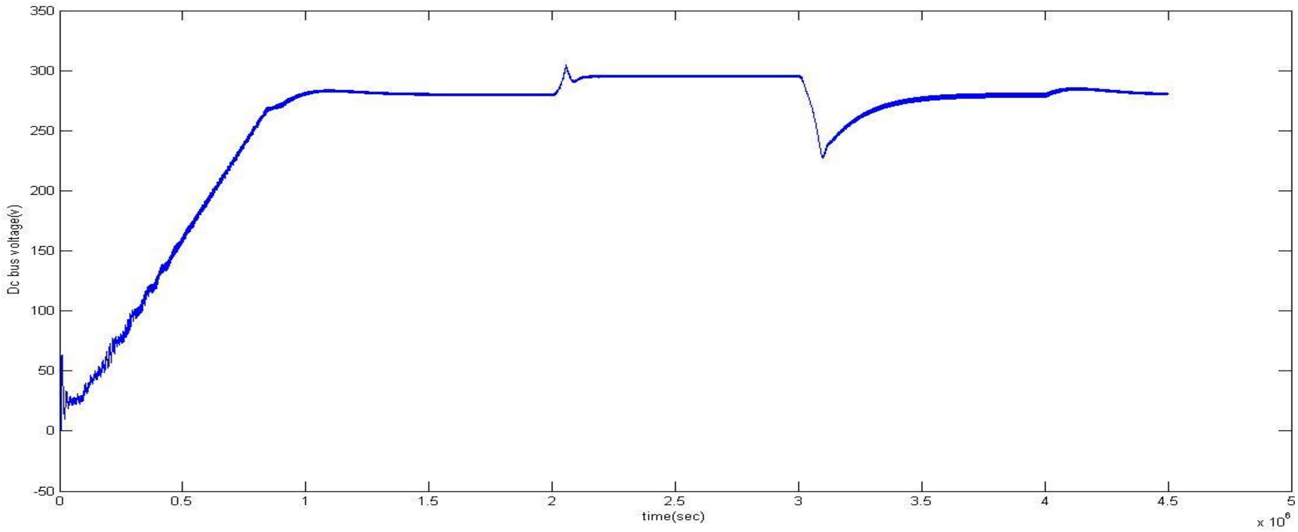

Figure 4.11: Variation of DC bus voltage of a 3-ϕ in case of open loop PI control for constant V/f control method

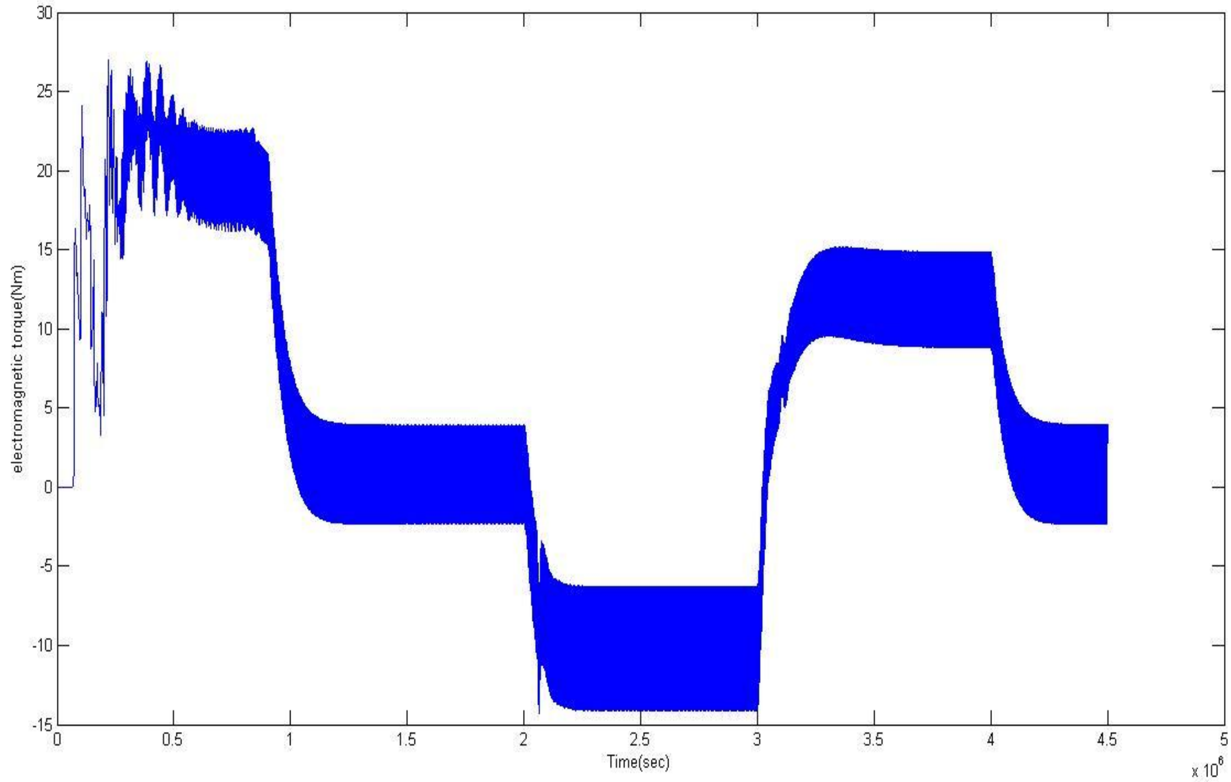

Figure 4.12: Variation of Torque of a 3-ϕ in case of open loop PI control for constant V/f control method

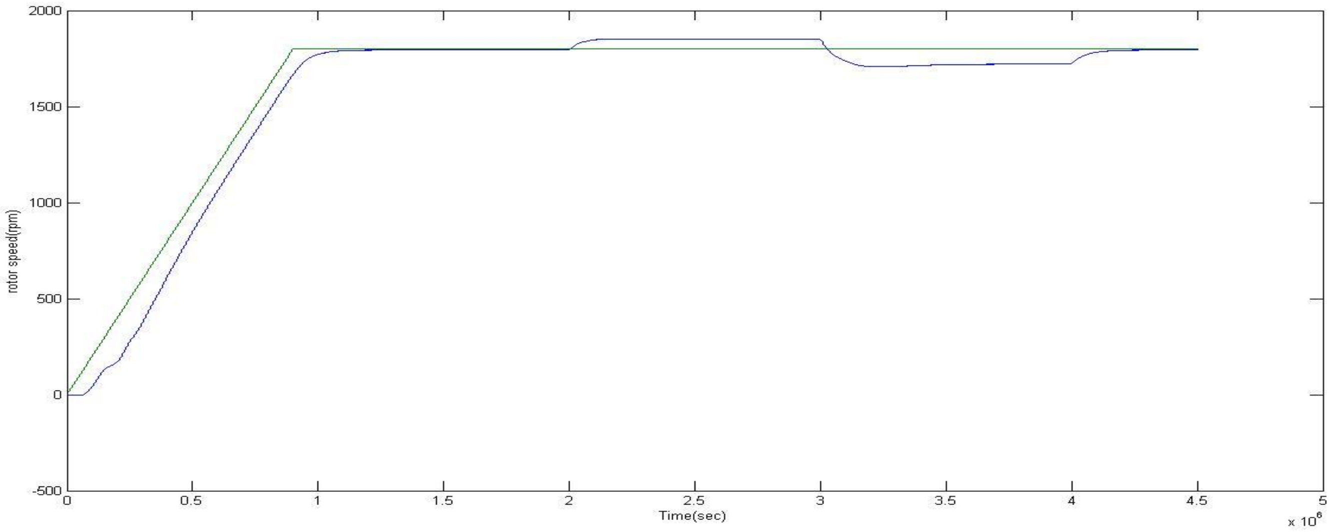

Figure 4.13: Variation of Rotor Speed of a 3-ϕ in case of open loop PI control for constant V/f control method

4.3.3 Closed Loop V/f speed control method using PI controller

A SIMULINK block was created to analyse the close loop constant V/f control method using PI controller and the Stator current (Figure 4.15), DC voltage (Figure 4.16), Electromagnetic torque (Figure 4.17) and Rotor speed (Figure 4.18) were plotted against time. The SIMULINK block is given below followed by the outcomes.

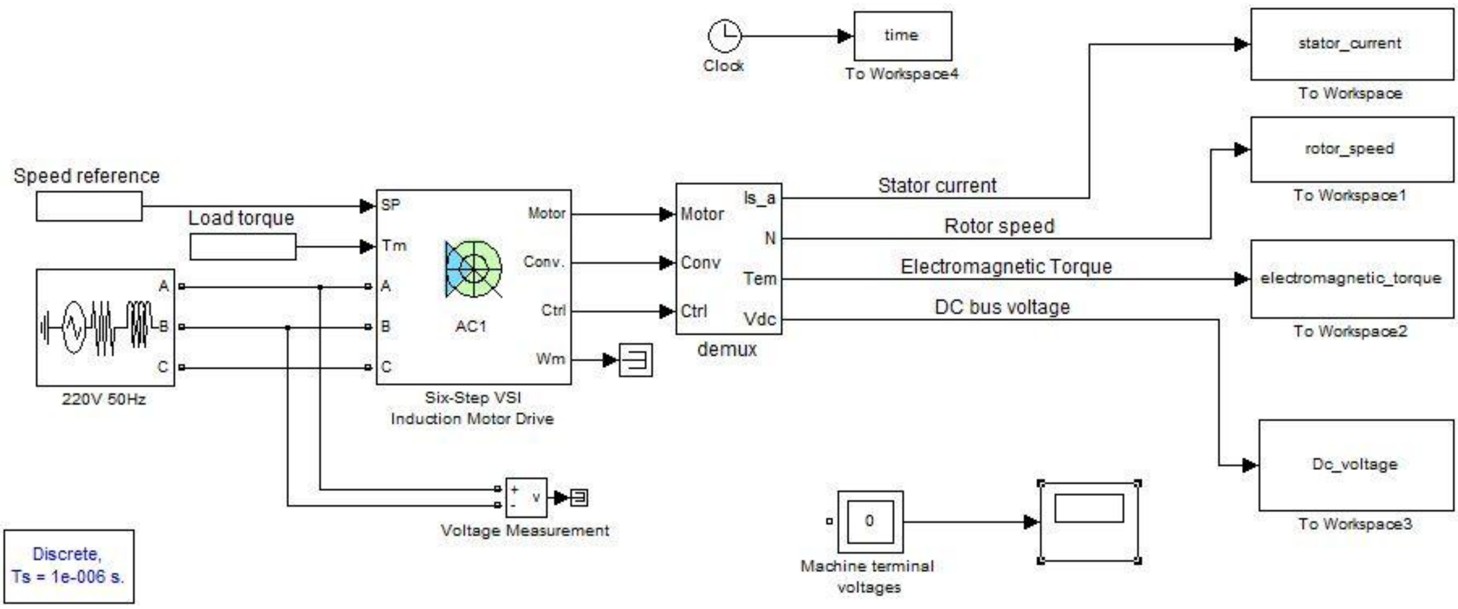

Figure 4.14: SIMULINK block of close loop constant V/f speed control using PI controller

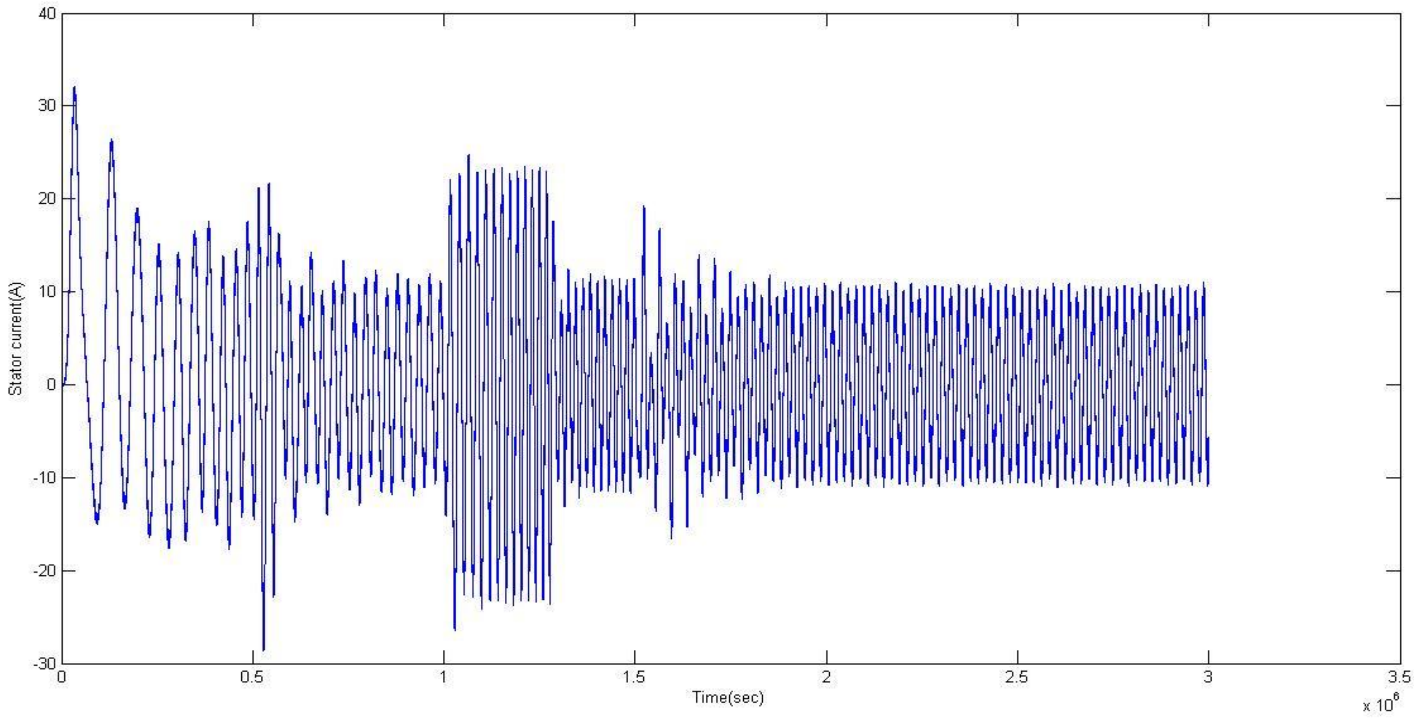

Figure 4.15: Variation of Stator current of a 3-ϕ in case of closed loop PI control for constant V/f control method

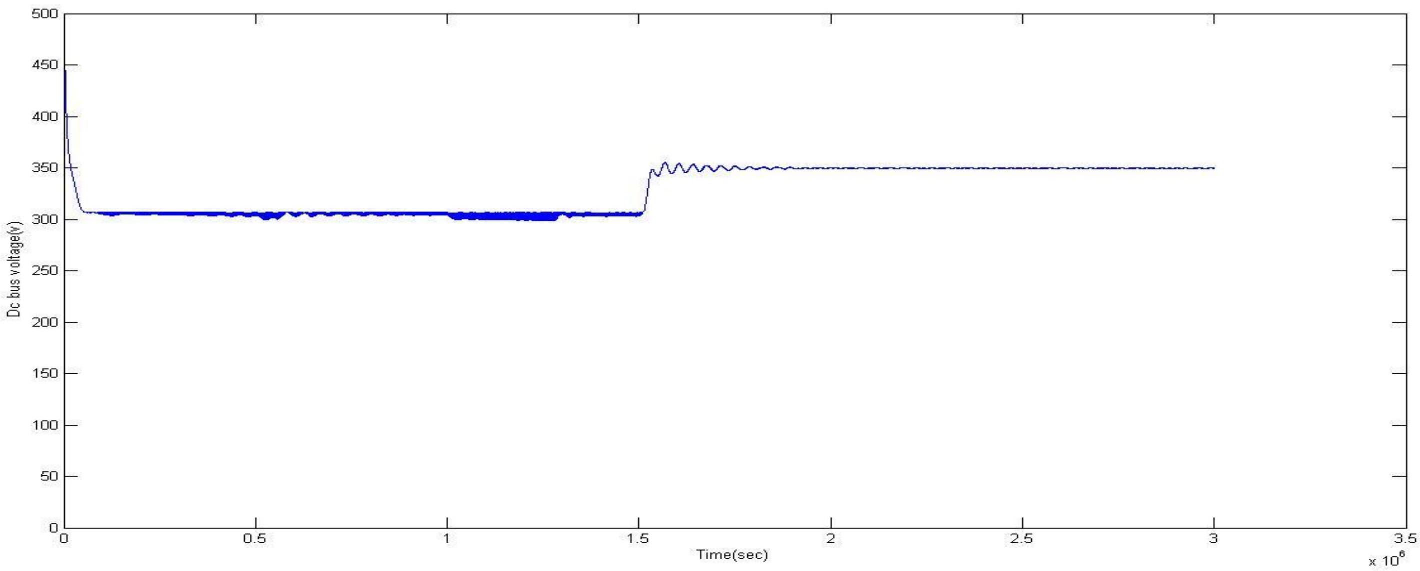

Figure 4.16: Variation of DC Bus Voltage of a 3-ϕ in case of closed loop PI control for constant V/f control method

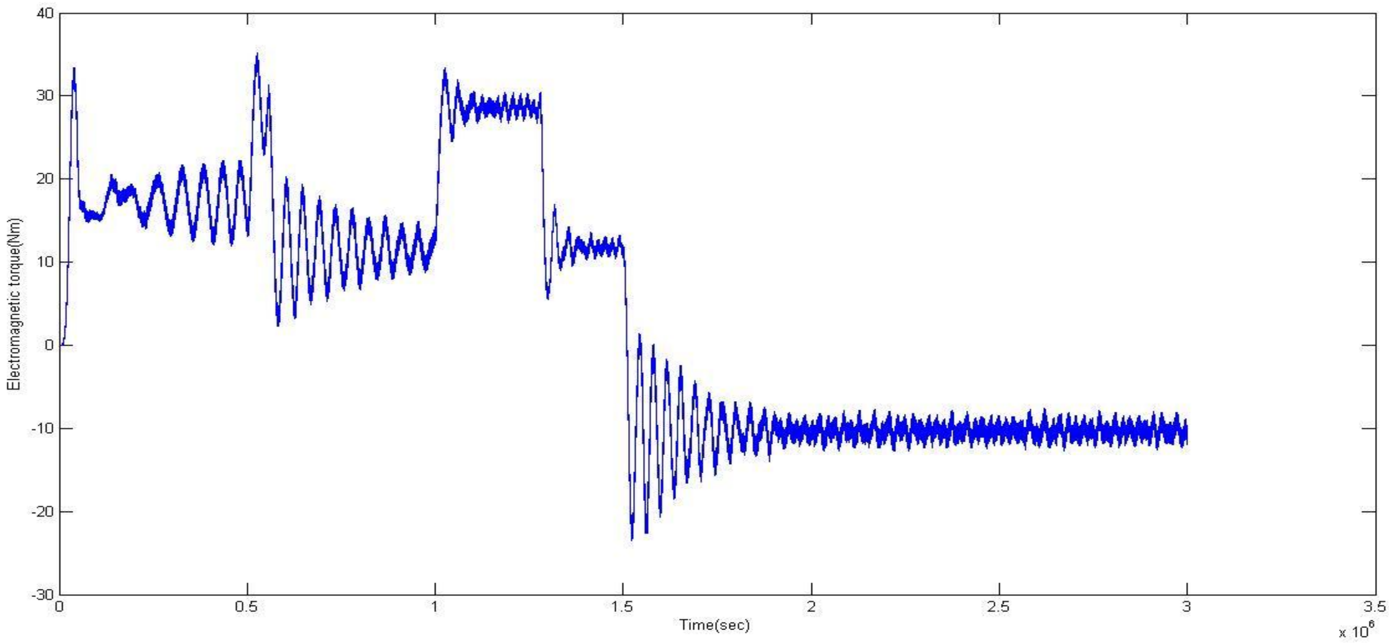

Figure 4.17: Variation of Torque of a 3-ϕ in case of closed loop PI control for constant V/f control method

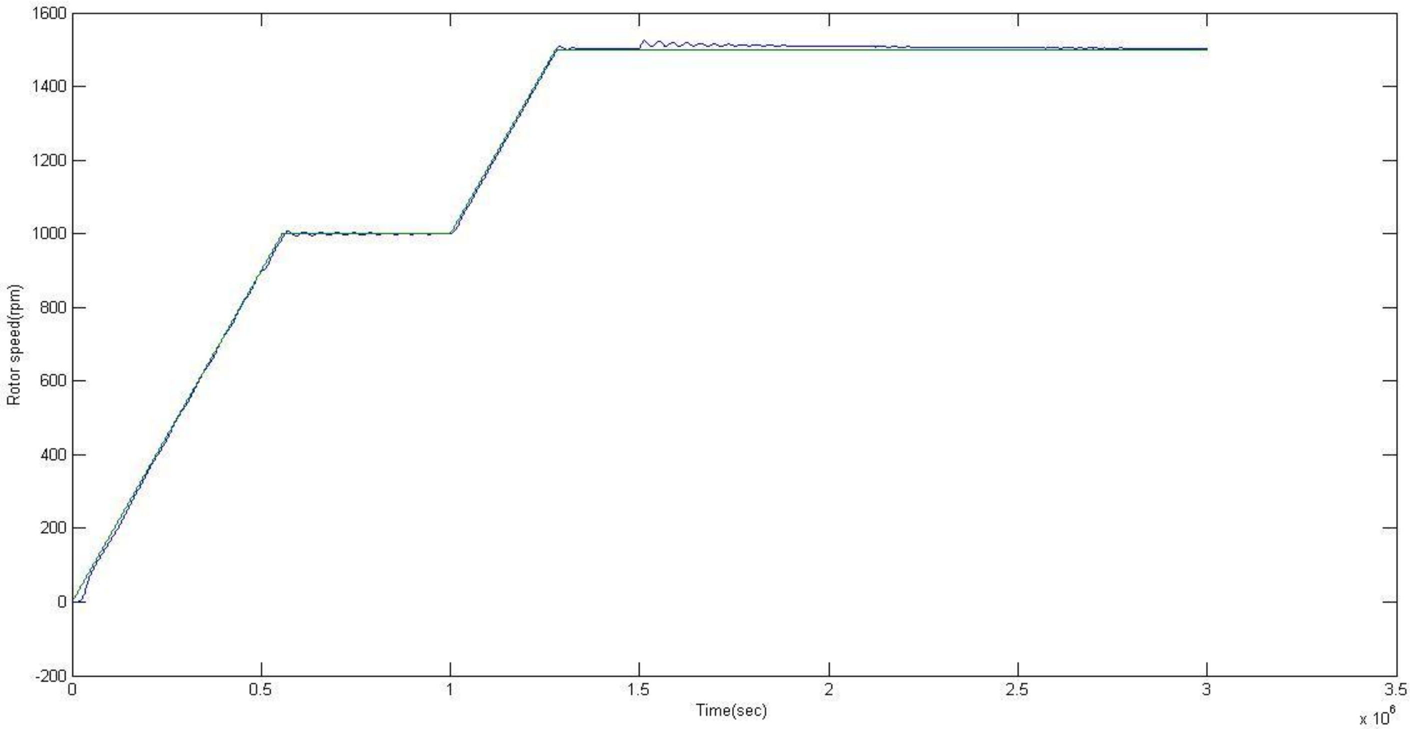

Figure 4.18: Variation of Rotor Speed of a 3-ϕ in case of closed loop PI control for constant V/f control method

4.4 Vector Control Method

The induction motor is the most widely used electrical motor due to its rugged structure, low cost and reliability. However, the nonlinearity in the Torque-Voltage relationship of an IM makes its analysis difficult. Also it is a fifth order system making its dynamic response poor. Development of Vector Control analysis has enabled us to get as good dynamic performance from an IM as a dc motor. The torque and the flux components can be controlled independently using vector control just like in a dc motor.

In order to analyse vector control, we need to develop a dynamic model of the IM. This is done by converting the 3-ϕ quantities into 2-axes system called the d-axis and the q-axis. Such a conversion is called axes transformation. The d-q axes can be chosen to be stationary or rotating. Further, the rotating frame can either be the rotor oriented or magnetizing flux oriented. However, synchronous reference frame in which the d-axis is aligned with the rotor flux is found to be the most convenient from analysis point of view.

A major disadvantage of the per phase equivalent circuit analysis is that it is valid only if the three phase system is balanced. Any imbalance in the system leads to erroneous analysis. Even this problem is eradicated if we use the d-q model.

4.4.1 d-q Equivalent Circuit

In many cases, analysis of induction motors with space vector model is complicated due to the fact that we have to deal with variables of complex numbers. For any space vector Y, let us define two real quantities S_q and S_d as,

$$\mathbf{S = S_q - j\, S_d} \tag{4.1}$$

In other words,

$$\mathbf{S_q = Re\,(S) \text{ and } S_d = -\, Im\,(S)}$$

Figure 4.9 illustrates the relationship between d-q axis and stationary a-b-c frame. It should be noted that d- and q-axes are defined on a rotating reference frame at the speed of ω_a with respect to fixed a-b-c frame.

4.4.2 Axes Transformation

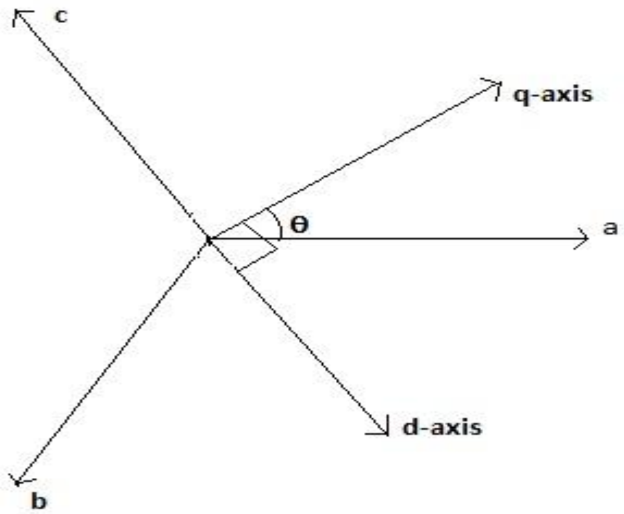

Figure 4.19: Angular relationships between reference axes

$$\begin{bmatrix} V_{qs}^{a} \\ V_{qs}^{a} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s+L_{sp} & \omega_a L_s & L_{mp} & \omega_s L_m \\ -\omega_a L_s & R_s+L_{sp} & -\omega_a L_m & L_{mp} \\ L_{mp} & -(\omega_a-\omega_0)L_m & R_r+L_{rp} & -(\omega-\omega_0)L_r \\ -(\omega_a-\omega_0)L_m & L_{mp} & -(\omega-\omega_0)L_r & R_r+L_{rp} \end{bmatrix} \begin{bmatrix} I_{qs}^{a} \\ I_{ds}^{a} \\ I_{qr}^{a} \\ I_{dr}^{a} \end{bmatrix} \quad (4.2)$$

Substituting $\omega_a = 0$, the above equation can be written as below: (This is called stationary reference frame)

$$\begin{bmatrix} V_{qs}^{a} \\ V_{qs}^{a} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s+L_{sp} & 0 & L_{mp} & 0 \\ 0 & R_s+L_{sp} & 0 & L_{mp} \\ L_{mp} & -\omega_0 L_m & R_r+L_{rp} & -\omega_0 L_r \\ \omega_0 L_m & L_{mp} & \omega_0) L_r & R_r+L_{rp} \end{bmatrix} \begin{bmatrix} I_{qs}^{s} \\ I_{ds}^{s} \\ I_{qr}^{s} \\ I_{dr}^{s} \end{bmatrix} \quad (4.3)$$

Sometimes vector control includes calculation in rotor reference frame (frame is attached to the rotor rotating at ω_o). In this case, $\omega_a = \omega_o$ in equation 4.2. Hence the matrix will be changed as

$$\begin{bmatrix} V_{qs}^{a} \\ V_{qs}^{a} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s+L_{sp} & \omega_0 L_s & L_{mp} & \omega_0 L_m \\ -\omega_0 L_s & R_s+L_{sp} & -\omega_0 L_m & L_{mp} \\ L_{mp} & \omega_r L_m & R_r+L_{rp} & \omega_r L_r \\ -\omega_0 L_m & L_{mp} & -\omega_0 L_r & R_r+L_{rp} \end{bmatrix} \begin{bmatrix} I_{qs} \\ I_{ds} \\ I_{qr} \\ I_{dr} \end{bmatrix} \tag{4.4}$$

For dynamic simulation of induction motors, equation 4.3 or equation 4.4 may be used.

Also we have

$$\boldsymbol{Vqs = R_s\, I_{qs} + p\lambda_{qs} + \omega_s\, \lambda_{ds}} \tag{4.5}$$

$$\boldsymbol{Vds = R_s\, I_{ds} + p\, \lambda_{ds} - \omega_s\, \lambda_{qs}} \tag{4.6}$$

$$\boldsymbol{0 = R_r\, I_{qr} + p\lambda_{qr} + \omega_r\, \lambda_{dr}} \tag{4.7}$$

$$\boldsymbol{0 = R_r\, I_{dr} + p\, \lambda_{dr} - \omega_r\, \lambda_{qr}} \tag{4.8}$$

where flux linkage variables are defined by

$$\boldsymbol{\lambda_{qs} = L_s\, I_{qs} + L_m\, I_{qr}} \tag{4.9}$$

$$\boldsymbol{\lambda_{ds} = L_s\, I_{ds} + L_m\, I_{dr}} \tag{4.10}$$

$$\boldsymbol{\lambda_{qr} = L_m\, I_{qs} + L_r\, I_{qr}} \tag{4.11}$$

$$\boldsymbol{\lambda_{dr} = L_m\, I_{ds} + L_r\, I_{dr}} \tag{4.12}$$

3-ϕ quantities converted into d-q quantities can be expressed as:

$$\mathbf{Sqs = (2/3)\ Re\{exp(-j\theta a)\ (S_a + \alpha S_b + \alpha^2\ S_c)\}} \tag{4.13}$$

$$\mathbf{Sds = -\ (2/3)\ Im\{exp(-j\theta a)\ (S_a + \alpha S_b + \alpha^2 S_c)\}} \tag{4.14}$$

$$\begin{bmatrix} Y_q \\ Y_q \\ 0 \end{bmatrix} = (2/3) \begin{bmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ \sin\theta & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} Y_a \\ Y_b \\ Y_c \end{bmatrix} \tag{4.15}$$

and its inverse transform is given by

$$\begin{bmatrix} Y_a \\ Y_b \\ Y_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) & 1 \\ \cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} Y_q \\ Y_d \\ 0 \end{bmatrix} \quad (4.16)$$

For any frame of reference, in terms of space vector instantaneous input power can be written as,

$$\boldsymbol{P_i = (3/2)\, Re(V_s\, I_s')} \quad (4.17)$$

or

$$\boldsymbol{P_i = (3/2)\, [\, V_{ds}\, I_{ds} + V_{qs}\, I_{qs}\,]} \quad (4.18)$$

The reactive power Qi can also be defined as

$$\boldsymbol{Q_i = (3/2)\, I_m(V_s\, I_s')} \quad (4.19)$$

or

$$\boldsymbol{Q_i = (3/2)\, [\, V_{qs}\, I_{ds} - V_{ds}\, I_{qs}\,]} \quad (4.20)$$

Torque in terms of d-q parameters is given by,

$$\boldsymbol{T_e} = \frac{3}{2}\boldsymbol{P}\frac{L_m}{L_r}(\boldsymbol{\lambda_{dr} i_{qs} - \lambda_{qr} i_{ds}}) \quad (4.21)$$

A MATLAB code was developed to observe the variations in q-axis and d-axis stator currents with change in stator voltage for a three phase induction motor. The MATLAB code is given in Appendix 5 and the machine parameters are given in table 2 at the end of the chapter. Following graphs were obtained:

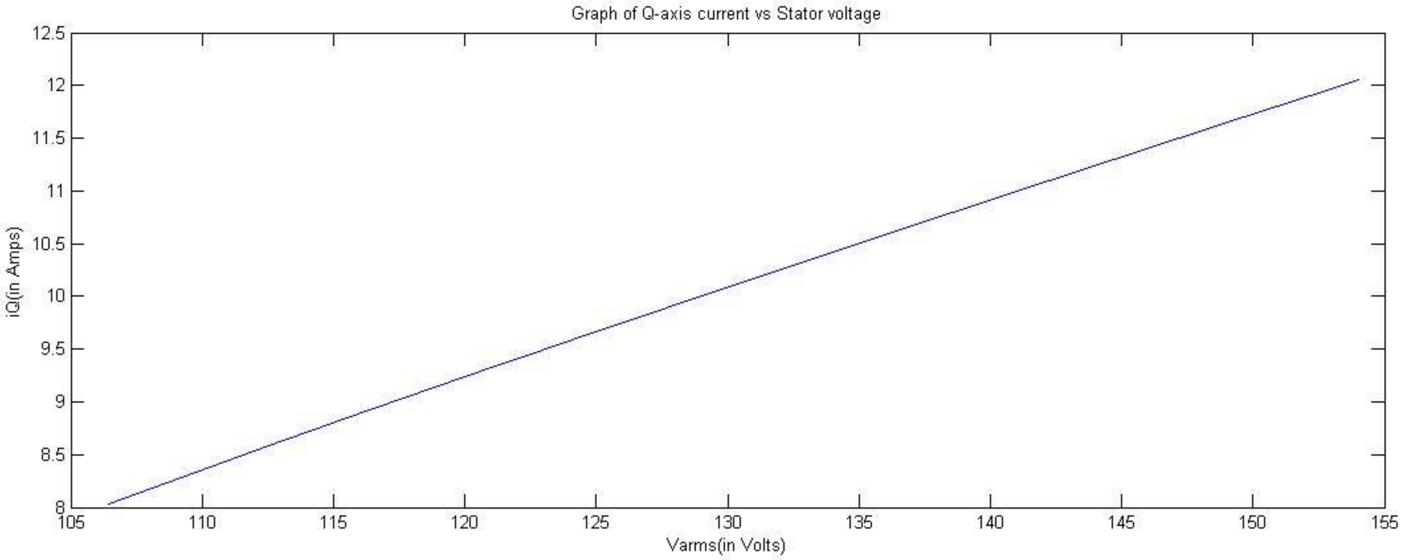

Figure 4.20: Variation of q-axis stator current with change in stator voltage

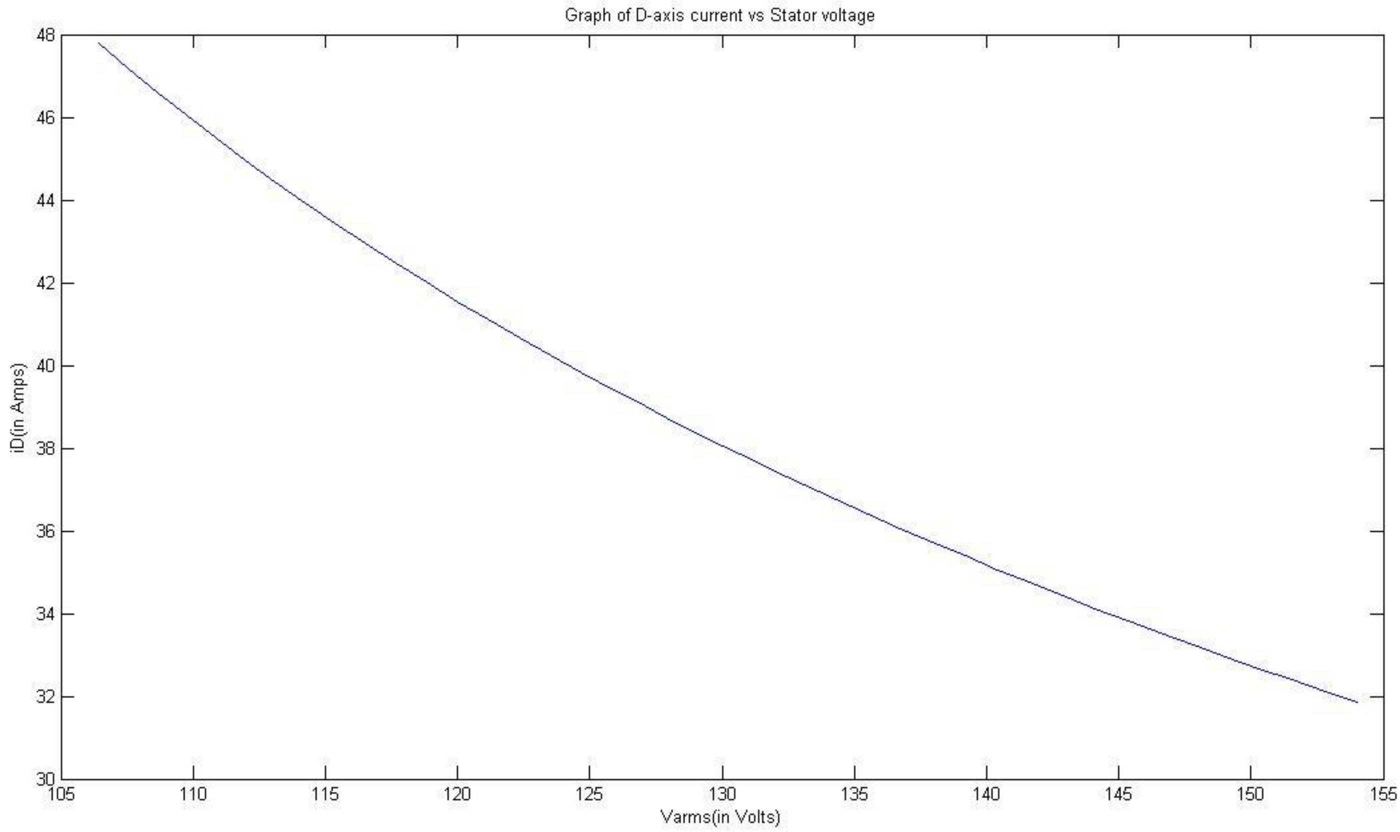

Figure 4.21: Variation of d-axis stator current with change in stator voltage

Table 1: Machine details used in MATLAB codes execution for variable rotor resistance, variable stator voltage and constant V/f control

RMS value of supply voltage (line-to-line)	415 Volts*
Number of poles	4
Stator resistance	0.075 ohm
Rotor resistance	0.1 ohm**
Frequency	50 Hz***
Stator leakage reactance at 50 Hz frequency	0.45 ohm
Rotor leakage reactance at 50 Hz frequency	0.45 ohm
V/f ratio (**ONLY FOR CONTANT V/f CONTROL)**	8.3

***** For Variable stator voltage and constant V/f methods, different values of supply voltage are given in the respective graphs (Figure 4.2 and Figure 4.3, respectively).

** For Variable rotor resistance method, different values of rotor resistance are given in the graph (Figure 4.1).

*** For constant V/f method, different values of supply frequency were used such that V/f ratio remained constant at 8.3.

Table 2: Motor rating and parameters used in MATLAB code execution for Vector control method

Rated Power	12 KW
Rated Stator Voltage (line to line)	230 V RMS
Operation Frequency	50 Hz
Number of Poles	4
Stator Resistance	0.095 ohms
Rotor Resistance	0.2 ohms
Stator Reactance	0.68 ohms
Rotor Reactance	0.672 ohms
Magnetizing Reactance	18.7 ohms

CHAPTER 5

CONCLUSIONS

Torque-Speed characteristics for different methods of speed control of an IM were obtained and analysed by developing MATLAB codes.

In rotor resistance control method the starting torque can be varied with the variation of rotor resistance. The maximum torque however, remains unaffected. Thus for operations requiring high starting torque, the rotor resistance can be varied to even obtain the maximum torque during starting. But simultaneously the copper losses will increase due to increase of resistance. So this method is highly inefficient and cannot be used throughout the operation.

In variable supply voltage control method of speed control, the maximum torque decreases with the decrease of supply voltage and thus the motor remains underutilized. So even this method cannot be used for good performance.

In constant $\frac{V}{f}$ control, by use of rectifier and PWM inverter, we can vary the supply voltage as well as the supply frequency such that the ratio $\frac{V}{f}$ remains constant so that the flux remains constant too. So we can get different operating zone for various speeds and torques and also we can get different synchronous speed with almost same maximum torque. Thus the motor is completely utilized and also we have a good range of speed control.

Also from the SIMULINK model for the starting of an induction motor with varying parameters, it was deduced that the stator resistance must be kept as low as possible so as to reduce the steady state time during starting and also to obtain a smoother start. Increasing the rotor resistance leads to increase in the starting torque (maximum torque occurs at a lesser speed) however, it also leads to a jerky start. Decreasing the inductance (either rotor or stator) lets the machine achieve its steady state quicker with slightly lesser jerks.

The traditional per phase equivalent circuit analysis of an induction motor has the disadvantage that it is valid only if the system is a balanced one. Any imbalance in the system leads to erroneous analysis. Also the dynamic response of the motor cannot be obtained from the per phase equivalent circuit. The vector control method or the d-q axes model leads to a simpler analysis of an induction motor. A d-q axes model with the d-axis aligned along the synchronously rotating rotor frame, leads to the decoupled analysis where the torque and the flux components can be independently controlled just like in case of a dc motor.

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APPENDICES

Appendix 1: MATLAB Code for Speed Control of 3-ϕ Induction motor using Variable Rotor Resistance

```
function out = inductionvarRr()
Vl1=input('Enter the Suppy Voltage (line to line) RMS value: ');
P=input('Enter the number of poles: ');
Rs=input('Stator Resistance: ');
Rr1=input('Enter the first Rotor Resistance: ');
Rr2=input('Enter the second Rotor Resistance: ');
Rr3=input('Enter the third Rotor Resistance: ');
Rr4=input('Enter the fourth Rotor Resistance: ');
Rr5=input('Enter the fifth Rotor Resistance: ');
Xs=input('Stator Leakage Reactance @ 50 Hz frequecny: ');
Xr=input('Rotor Leakage Reactance @ 50 Hz frequecny: ');

Ls=Xs/(2*pi*50);
Lr=Xr/(2*pi*50);

Wsync1=4*pi*50/P;

Tmf2=zeros(Wsync1*500+1,1);
Tmf3=zeros(Wsync1*500+1,1);
Tmf4=zeros(Wsync1*500+1,1);
Tmf5=zeros(Wsync1*500+1,1);
Tmf1=zeros(Wsync1*500+1,1);

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf1(m)=(3*(((Vl1^2)*Rr1/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr1/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1); %star connected
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf2(m)=(3*(((Vl1^2)*Rr2/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr2/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf3(m)=(3*(((Vl1^2)*Rr3/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr3/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end
```

```
m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf4(m)=(3*(((Vl1^2)*Rr4/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr4/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf5(m)=(3*(((Vl1^2)*Rr5/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr5/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

plot(Tmf1);
hold on;
plot(Tmf2);
plot(Tmf3);
plot(Tmf4);
plot(Tmf5);
hold off;

ylabel('Torque(N-m)');
xlabel('Rotor Speed(Rad/s)');
end
```

Appendix 2: MATLAB Code for Speed Control of 3-ϕ Induction motor using Variable Stator Voltage

```
function out = inductionvarV()
Vl1=input('Enter the first Suppy Voltage (line to line) RMS value: ');
Vl2=input('Enter the second Suppy Voltage (line to line) RMS value: ');
Vl3=input('Enter the third Suppy Voltage (line to line) RMS value: ');
Vl4=input('Enter the fourth Suppy Voltage (line to line) RMS value: ');
Vl5=input('Enter the fifth Suppy Voltage (line to line) RMS value: ');
P=input('Enter the number of poles: ');
Rs=input('Stator Resistance: ');
Rr=input('Rotor Resistance: ');
Xs=input('Stator Leakage Reactance @ 50 Hz frequecny: ');
Xr=input('Rotor Leakage Reactance @ 50 Hz frequecny: ');

Ls=Xs/(2*pi*50);
Lr=Xr/(2*pi*50);

Wsync1=4*pi*50/P;

Tmf2=zeros(Wsync1*500+1,1);
Tmf3=zeros(Wsync1*500+1,1);
Tmf4=zeros(Wsync1*500+1,1);
Tmf5=zeros(Wsync1*500+1,1);
Tmf1=zeros(Wsync1*500+1,1);

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf1(m)=(3*(((Vl1^2)*Rr/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1); %star connected
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf2(m)=(3*(((Vl2^2)*Rr/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf3(m)=(3*(((Vl3^2)*Rr/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1
```

```
    Tmf4(m)=(3*(((Vl4^2)*Rr/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf5(m)=(3*(((Vl5^2)*Rr/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1);
    m=m+1;
end

plot(Tmf1);
hold on;
plot(Tmf2);
plot(Tmf3);
plot(Tmf4);
plot(Tmf5);
hold off;

ylabel('Torque(N-m)');
xlabel('Rotor Speed(Rad/s)');
end
```

Appendix 3: MATLAB Code for Speed Control of 3-ϕ Induction motor using Constant V/f control

```
function out = inductionconstVf()
Vll=input('Suppy Voltage (line to line) RMS value @ 50 Hz: ');
f2=input('Enter the second frequency: ');
f3=input('Enter the third frequency: ');
f4=input('Enter the fourth frequency: ');
f5=input('Enter the fifth frequency: ');
P=input('Enter the number of poles: ');
Rs=input('Stator Resistance: ');
Rr=input('Rotor Resistance: ');
Xs=input('Stator Leakage Reactance @ 50 Hz frequecny: ');
Xr=input('Rotor Leakage Reactance @ 50 Hz frequecny: ');

Ls=Xs/(2*pi*50);
Lr=Xr/(2*pi*50);

Vlnf1=Vll/(3^0.5);
Vlnf2=Vlnf1*f2/50;
Vlnf3=Vlnf1*f3/50;
Vlnf4=Vlnf1*f4/50;
Vlnf5=Vlnf1*f5/50;

Wsync1=4*pi*50/P;
Wsync2=4*pi*f2/P;
Wsync3=4*pi*f3/P;
Wsync4=4*pi*f4/P;
Wsync5=4*pi*f5/P;

Tmf2=zeros(Wsync2*500+1,1);
Tmf3=zeros(Wsync3*500+1,1);
Tmf4=zeros(Wsync4*500+1,1);
Tmf5=zeros(Wsync5*500+1,1);
Tmf1=zeros(Wsync1*500+1,1);

m=1;

for Wrotor1=0:0.002:Wsync1

    Tmf1(m)=(3*(((Vlnf1^2)*Rr/((Wsync1-Wrotor1)/Wsync1))/((Rs+Rr/((Wsync1-
Wrotor1)/Wsync1))^2+(2*pi*50*Ls+2*pi*50*Lr)^2))/Wsync1); %star connected
    m=m+1;
end

m=1;

for Wrotor2=0:0.002:Wsync2

    Tmf2(m)=(3*(((Vlnf2^2)*Rr/((Wsync2-Wrotor2)/Wsync2))/((Rs+Rr/((Wsync2-
Wrotor2)/Wsync2))^2+(2*pi*f2*Ls+2*pi*f2*Lr)^2))/Wsync2);
    m=m+1;
end

m=1;
```

```
for Wrotor3=0:0.002:Wsync3

    Tmf3(m)=(3*(((Vlnf3^2)*Rr/((Wsync3-Wrotor3)/Wsync3))/((Rs+Rr/((Wsync3-
Wrotor3)/Wsync3))^2+(2*pi*f3*Ls+2*pi*f3*Lr)^2))/Wsync3);
    m=m+1;
end

m=1;

for Wrotor4=0:0.002:Wsync4

    Tmf4(m)=(3*(((Vlnf4^2)*Rr/((Wsync4-Wrotor4)/Wsync4))/((Rs+Rr/((Wsync4-
Wrotor4)/Wsync4))^2+(2*pi*f4*Ls+2*pi*f4*Lr)^2))/Wsync4);
    m=m+1;
end

m=1;

for Wrotor5=0:0.002:Wsync5

    Tmf5(m)=(3*(((Vlnf5^2)*Rr/((Wsync5-Wrotor5)/Wsync5))/((Rs+Rr/((Wsync5-
Wrotor5)/Wsync5))^2+(2*pi*f5*Ls+2*pi*f5*Lr)^2))/Wsync5);
    m=m+1;
end

plot(Tmf1);
hold on;
plot(Tmf2);
plot(Tmf3);
plot(Tmf4);
plot(Tmf5);
hold off;

ylabel('Torque(N-m)');
xlabel('Rotor Speed(Rad/s) * 100');
end
```

Appendix 4: MATLAB Code for Closed Loop Speed Control of 3-ϕ Induction motor using Constant V/f

```
function out = inductionconstVfclosed()

Input1;

Tmm=[];
Wrotormat=[];

Ls=Xs/(2*pi*50);
Lr=Xr/(2*pi*50);

Vfratio=Vratedph/200; %Constant V/f ratio = Rated Voltage/Maximum frequency
that is applied (taken as 200 Hz)

%Find the value of Frequency at which the motot shall be started so that
the given operating point (Tlstarting,Wref) lies in the stable zone

if Tlstarting==0

    Wsync=Wref;
    f=Wsync*P/120;
    V=Vfratio*f;

else
    for f=1:0.001:200

        Wsync=120*f/P;
        s=(Wsync-Wref)/Wsync;
        sm=(Rr/((Rs^2+(2*pi*f*Ls+2*pi*f*Lr)^2)^0.5));

        if Wref<Wsync && s<sm %to make sure that the operating point lies
in the stable zone
            f=f;
            V=Vfratio*f;

            if Tlstarting>=(0.95*(3*(((V^2)*Rr/((Wsync-
Wref)/Wsync))/((Rs+Rr/((Wsync-
Wref)/Wsync))^2+(2*pi*f*Ls+2*pi*f*Lr)^2))/Wsync)) &&
Tlstarting<=(1.05*(3*(((V^2)*Rr/((Wsync-Wref)/Wsync))/((Rs+Rr/((Wsync-
Wref)/Wsync))^2+(2*pi*f*Ls+2*pi*f*Lr)^2))/Wsync))
                break;
            end
        end
    end
end

Tm=zeros(100001,1);
Wrot=zeros(100001,1);
m=1;

%Store the values of torque at different rotor speeds to plot the Torque-
Speed characteristics

for Wrotor=0:Wsync/100000:Wsync
```

```
    Tm(m)=(3*(((V^2)*Rr/((Wsync-Wrotor)/Wsync))/((Rs+Rr/((Wsync-
Wrotor)/Wsync))^2+(2*pi*f*Ls+2*pi*f*Lr)^2))/Wsync);
    if Tm(m)<0
        Tm(m)=0;
    end
    Wrot(m)=Wrotor;
    m=m+1;
end

Tmax=(3*(V^2/(Rs+(Rs^2+(2*pi*f*Ls+2*pi*f*Lr)^2)^0.5))/(2*Wsync)); % Maximum
Torque the given motor can deliver for the current values of V and f

% Vary the Load Torque From 0.1 to Tmax with a step of Tmax/10 and apply
the closed loop P control to maintain the motor speed at Wref for any
permissible values of load torque

for Tl=0.1:Tmax/10:Tmax

    Tmm=[Tmm Tm];
    Wrotormat=[Wrotormat Wrot];

    for a=100001:-1:1

        if (Tm(a)*0.95)<=Tl && Tl<=(Tm(a)*1.05)
            W=Wrot(a);
            break;
        end
    end

    Werror=Wref-W; % Error in speed to be corrected

    n=1;

    f=f+(Werror*P/120); % The frequency and hence the Speed Corrected
Proportionately (ie P controller used)

    Wsync=120*f/P;

    V=Vfratio*f;

% Store the values of torque at different rotor speeds to plot the Torque-
Speed characteristics

    for Wrotor=0:Wsync/100000:Wsync

        Tm(n)=(3*(((V^2)*Rr/((Wsync-Wrotor)/Wsync))/((Rs+Rr/((Wsync-
Wrotor)/Wsync))^2+(2*pi*f*Ls+2*pi*f*Lr)^2))/Wsync); %Star connected
        if Tm(n)<0
            Tm(n)=0;
        end
        Wrot(n)=Wrotor;
        n=n+1;
    end
end

[c,d]=size(Tmm);
[e,h]=size(Wrotormat);
```

```
figure;

% Plot the Torque-Speed Characteristics of the motor for various values of
Load Torque

hold on;

for g=1:1:d
    plot(Wrotormat(:,g),Tmm(:,g));
end

hold off;

end
```

Appendix 5: MATLAB Code to observe the variations in q-axis and d-axis stator currents with change in stator voltage for a 3-ϕ induction motor

```
function out = vectorcontrol( )
clc;
clear all;
%Motor detalis (Rated)
P = 12*10^-3;
V = 230;
Va = 230/sqrt(3) ;
fe = 50;
We = 2*pi*fe;
Lambda = sqrt(2)*Va/We;
I= P/(sqrt(3)*V) ;
Ipeakbase = sqrt(2)*I;
poles=4 ;
%Paramteres for 50-Hz motor
VI0 = V/sqrt(3) ;
X10 = 0.67;
X20 = 0.67;
Xm0 = 18.0;
R1 = 0.1;
R2 = 0.2;
%d-q parameters
Lm = Xm0/We;
LS = Lm + X10/We;
LR = Lm + X20/We;
Ra = R1;
RaR = R2 ;
% Operating point
Wm = 2*n*pi/60;
Wme = (poles/2)*Wm;
Pmech = 9.7*10-3;
Tmech = Pmech/Wm;
Te=zeros(1001,1);

for n = 1:1:41
lambda_D_R = (0.8 + (n-1)*0.4/40)*Lambda;
iQ(n) = (2/3) * (2/poles) * (LR/Lm) * (Tmech/lambdaDR) ;
iD(n) = (lambdaDR/Lm) ;
iQm(n) = - (Lm/LR)*iQ(n);
Ia(n) =sqrt((iD(n)^2 + iQ(n)^2)/2) ;
We(n) = Wme - (RaR/LR)*(iQ(n)/iD(n)) ;
fe(n) = We(n)*poles/120 ;
Varms(n) = sqrt( ((Ra*iD(n)-We(n)*(LS-Lm^2/LR)*iQ(n)) ^2 +(Ra*iQ(n)+
We(n)*LS*iD(n))^2) /2) ;
end
plot (Varms,iQ)
figure
plot(Varms,iD)
end
```